Ad hoc Wireless Networks with Femto-Cell Deployment: A Study

Zubin Rustam Bharucha

A thesis submitted for the degree of Doctor of Philosophy.
The University of Edinburgh.
2010
Abstract

Nowadays, with a worldwide market penetration of over 50% in the mobile telecommunications sector, there is also an unrelenting demand from the subscribers for ever increasing transmission rates and availability of broadband-like experience on the handset. Due to this, research in next-generation networks is rife. Such systems are expected to achieve peak data rates of up to 1 Gbps through the use of innovative technologies such as multiple-input and multiple-output (MIMO) and orthogonal frequency division multiple access (OFDMA). Two more ways of boosting capacity have also been identified: shrinking cell sizes and greater reuse of resources in the same area. This forms the foundation of the research presented in this thesis.

For operators, the costs involved with planning and deploying additional network infrastructure to provide a dense coverage of small, high capacity cells cannot be justified. Femto-cells, however, promise to fulfil this function. These are user-deployed mini base stations (BSs), known as home evolved NodeBs (HeNBs), which are envisaged to be commonplace in homes and offices in the coming years. Since they drastically reduce communication distances to user equipments (UEs) and reuse the resources already utilised in the macro-cell, they help boost the system capacity significantly. However, there are issues to be addressed with the deployment of femto-cells, such as increased interference to the system and methods of access. These and other problems are discussed and analysed in this thesis. One of the first steps towards femto-cell research has been the study of the time division duplex (TDD) underlay concept, whereby an indoor UE acts as a relay between the evolved NodeB (eNB) and other indoor UEs. In order to gain a deeper understanding of how and under what conditions such a self-organising network can be deployed, a mathematical analysis of the distribution of path losses in a network of uniformly distributed nodes has been performed. In connection with this, research has also been done in the identification of well connected nodes in such networks. Next, extensive simulations on traditional cellular networks with embedded femto-cells have been carried out in order to demonstrate the benefits of femto-cell deployment. This research has shown that femto-cells can cause severe downlink (DL) interference to badly placed macro UEs. Finally, a novel interference avoiding technique that addresses this problem is investigated.
Declaration of Originality

I hereby declare that the research recorded in this thesis and the thesis itself was composed and originated entirely by myself in the Institute for Digital Communications at The University of Edinburgh and The School of Engineering and Sciences at Jacobs University.

Zubin Bharucha
Acknowledgments

I owe my undying and humble gratitude to my friends, scattered as they are, in Germany, the U.K., the U.S.A., Canada, Switzerland and India, for all the not-too-regular meet-ups with them, my beautiful and infinitely patient girlfriend, Julia, for keeping my spirits up despite all she has had to put up with and most importantly, my parents for all the sacrifices they have made and for all the freedom they have given me in doing what I want to do. I owe a lot to Harald, my supervisor, for believing in me and helping me stay on track over the years. Without these people, I would have lost both my sanity and will to continue.

Special thanks also go to Sinan for helping me, especially in connection with the research presented in Chapter 4, Birendra and Rami for the numerous helpful discussions we have had over the years, my friends at the Institute for Digital Communications (IDCoM), my colleagues at DOCOMO Euro-Labs, especially Gunther, for helping me out whenever I annoyed them with questions and Harald Burchardt for building on my work.

Finally, without the financial backing of Jacobs University, the Deutsche Forschungsgemeinschaft (DFG), DOCOMO Euro-Labs and the School of Engineering at The University of Edinburgh, none of this would have been possible.
Contents

Declaration of Originality ........................................ iii
Acknowledgments ..................................................... iv
Contents ........................................................................ v
List of figures ................................................................ viii
List of tables ............................................................. x
Acronyms and abbreviations ........................................ xi
Nomenclature .............................................................. xvi

1 Introduction ............................................................. 1
  1.1 About this Thesis ................................................... 1
  1.2 The Case for Femto-cells .......................................... 2
  1.3 Contributions ........................................................ 4
  1.4 Thesis Layout ........................................................ 5

2 Motivation and Background ......................................... 7
  2.1 An Historical Overview: Towards LTE ...................... 7
  2.2 Overview of Concepts ............................................. 10
    2.2.1 Methods of Increasing Data Rates ...................... 10
    2.2.2 Frequency Reuse ............................................. 13
    2.2.3 Duplexing Techniques ...................................... 16
    2.2.4 Multiple Access Techniques ............................. 20
  2.3 Calculating Capacity .............................................. 28
  2.4 Motivation ............................................................ 31
  2.5 Summary .............................................................. 36

3 The TDD Underlay Concept ......................................... 38
  3.1 Overview ............................................................. 38
  3.2 Introduction ........................................................ 39
    3.2.1 System Setup ............................................... 42
    3.2.2 Simulation Model .......................................... 46
    3.2.3 Performance Metrics ...................................... 48
    3.2.4 Results ....................................................... 49
  3.3 Summary .............................................................. 51

4 A Mathematical Treatment of Hotspots ........................ 54
Contents

4.1 Overview ................................................. 54
4.2 Path Loss Distribution within a Hotspot ................. 55
   4.2.1 Background ........................................ 55
   4.2.2 Path Loss Distribution for Uniformly Distributed Users in a Circle .. 56
   4.2.3 Results ............................................. 57
4.3 Star-node Detection ...................................... 58
   4.3.1 Background ........................................ 58
   4.3.2 Random Graphs ..................................... 62
   4.3.3 Star-Node Detection ................................. 62
   4.3.4 Results ............................................. 67
4.4 Summary .................................................. 71

5 Femto-cell Deployment .................................... 73
   5.1 Overview ............................................. 73
   5.2 Introduction .......................................... 74
   5.3 Access Control Strategies .............................. 76
   5.4 System Model and Simulation Setup ..................... 78
      5.4.1 Capacity Calculation ............................. 78
      5.4.2 Channel Model .................................... 80
      5.4.3 Path Loss Models ................................. 81
      5.4.4 Uplink Power Control ............................. 83
      5.4.5 User Distribution ................................. 84
   5.5 Results ................................................ 86
      5.5.1 Downlink .......................................... 88
      5.5.2 Uplink ............................................. 90
      5.5.3 Set B: Affected Macro UEs ....................... 92
   5.6 Summary ................................................ 95

6 Femto-cell Downlink Resource Partitioning ................ 96
   6.1 Overview ............................................. 96
   6.2 Introduction .......................................... 97
   6.3 Femto-Cell Resource Partitioning ..................... 99
      6.3.1 Downlink Interference Scenario for Closed-Access ............. 99
      6.3.2 Avoiding Femto-to-Macro Interference ................ 99
      6.3.3 Practical Implementation in LTE Systems .................. 102
   6.4 System-Level Simulation Setup ........................ 105
      6.4.1 System Model .................................... 105
      6.4.2 Path Loss Models ................................ 106
      6.4.3 User Distribution and Sectorised eNBs ............... 107
      6.4.4 Time Evolution ................................... 109
   6.5 Results ................................................ 109
   6.6 Summary ................................................ 116

7 Conclusions, Limitations and Future Work ................ 118
   7.1 Summary and Conclusions ............................. 118
   7.2 Limitations and Future Work .......................... 120
      7.2.1 Femto-cell Research ............................ 120
Contents

7.2.2 Star-node Research .................................................. 125

A Derivation of the pdf of Path Loss Distribution in a Circle .............. 127

B List of Publications ..................................................... 131
  B.1 Published ............................................................. 131
  B.2 Accepted ............................................................ 132
  B.3 3GPP Standardisation Contributions .................................. 132
  B.4 Patents ............................................................... 132

C Selected Publications ................................................... 133

References ................................................................. 196
# List of figures

1.1 Growth of mobile subscriptions .................................................. 2  
1.2 Global communications ICT developments .................................... 3  

2.1 Required $E_b/N_0$ as a function of the bandwidth utilisation, $\psi$ .............. 11  
2.2 The effects of multipath propagation and Doppler spread ....................... 12  
2.3 Frequency reuse ........................................................................... 14  
2.4 FDD concept ............................................................................... 17  
2.5 TDD concept ............................................................................... 18  
2.6 TDMA concept ............................................................................ 20  
2.7 FDMA concept ............................................................................ 21  
2.8 CDMA concept ............................................................................ 22  
2.9 OFDM concept ............................................................................. 23  
2.10 SC vs. MC comparison ................................................................. 23  
2.11 OFDM subcarrier spacing .............................................................. 24  
2.12 OFDM modulation ....................................................................... 25  
2.13 OFDM demodulation ................................................................. 25  
2.14 OFDMA grid .............................................................................. 26  
2.15 OFDMA allocation ................................................................. 27  
2.16 A DOCOMO HeNB ..................................................................... 34  
2.17 The femto-cell concept ............................................................... 35  

3.1 Hybrid division duplex .................................................................... 42  
3.2 The TDD underlay concept ............................................................ 43  
3.3 WINNER frame structure ............................................................... 44  
3.4 User distribution in simulation scenario .......................................... 47  
3.5 Hotspot capacity .......................................................................... 49  
3.6 Capacity gain through TDD underlay intra-hotspot communication .......... 50  
3.7 Spectral efficiencies in the proposed and benchmark systems ............. 51  
3.8 Bottleneck between the shorter GUE $\rightarrow$ UE link and the longer GUE $\rightarrow$ BS link ..... 52  

4.1 pdfs and CDFs of path loss distribution .......................................... 59  
4.2 Different node types ...................................................................... 61  
4.3 Relationship between $p$ and path loss ........................................... 63  
4.4 Non-asymptotic $K$-star-node detection theory explained .................... 66
<table>
<thead>
<tr>
<th>Figure Number</th>
<th>Figure Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5</td>
<td>Detection of at least one $K$-star-node</td>
<td>68</td>
</tr>
<tr>
<td>4.6</td>
<td>Detection of at least one $K$-star-node using tighter method</td>
<td>69</td>
</tr>
<tr>
<td>4.7</td>
<td>Detection of exactly one star-node</td>
<td>70</td>
</tr>
<tr>
<td>4.8</td>
<td>Detection of exactly 10 $K$-star-nodes</td>
<td>71</td>
</tr>
<tr>
<td>5.1</td>
<td>Different access methods with femto-cell deployment</td>
<td>77</td>
</tr>
<tr>
<td>5.2</td>
<td>LTE frame structure</td>
<td>79</td>
</tr>
<tr>
<td>5.3</td>
<td>$d_{out}$ and $d_{in}$ measurements</td>
<td>83</td>
</tr>
<tr>
<td>5.4</td>
<td>UL power control</td>
<td>84</td>
</tr>
<tr>
<td>5.5</td>
<td>Sample user distribution</td>
<td>85</td>
</tr>
<tr>
<td>5.6</td>
<td>Sum system capacity</td>
<td>86</td>
</tr>
<tr>
<td>5.7</td>
<td>DL capacity for Set A (femto) UEs</td>
<td>89</td>
</tr>
<tr>
<td>5.8</td>
<td>DL performance for Set A (macro) UEs</td>
<td>90</td>
</tr>
<tr>
<td>5.9</td>
<td>UL capacity for Set A (femto) UEs</td>
<td>91</td>
</tr>
<tr>
<td>5.10</td>
<td>UL performance for Set A (macro) UEs</td>
<td>92</td>
</tr>
<tr>
<td>5.11</td>
<td>Open and closed-access performance for Set B UEs</td>
<td>93</td>
</tr>
<tr>
<td>5.12</td>
<td>DL interference statistics for Set B UEs.</td>
<td>94</td>
</tr>
<tr>
<td>5.13</td>
<td>UL interference statistics for Set B UEs.</td>
<td>94</td>
</tr>
<tr>
<td>6.1</td>
<td>Resource partitioning concept</td>
<td>100</td>
</tr>
<tr>
<td>6.2</td>
<td>Effects of varying interference thresholds</td>
<td>101</td>
</tr>
<tr>
<td>6.3</td>
<td>Overall LTE architecture</td>
<td>103</td>
</tr>
<tr>
<td>6.4</td>
<td>Sample user distribution</td>
<td>108</td>
</tr>
<tr>
<td>6.5</td>
<td>DL interference for affected macro UEs</td>
<td>111</td>
</tr>
<tr>
<td>6.6</td>
<td>Overall DL macro user capacity</td>
<td>112</td>
</tr>
<tr>
<td>6.7</td>
<td>Femto DL user capacity</td>
<td>114</td>
</tr>
<tr>
<td>6.8</td>
<td>DL user capacity only for affected macro UEs</td>
<td>115</td>
</tr>
<tr>
<td>6.9</td>
<td>DL user capacity only for affected femto UEs</td>
<td>115</td>
</tr>
<tr>
<td>7.1</td>
<td>Control channel interference</td>
<td>121</td>
</tr>
<tr>
<td>7.2</td>
<td>Control and data regions in an LTE subframe</td>
<td>122</td>
</tr>
<tr>
<td>7.3</td>
<td>DL SINR for all macro UEs</td>
<td>124</td>
</tr>
<tr>
<td>7.4</td>
<td>DL SINR for all femto UEs</td>
<td>125</td>
</tr>
</tbody>
</table>
## List of tables

3.1 Simulation parameters for TDD underlay simulation ........................................ 47
4.1 Simulation parameters for path loss distribution simulation ................................ 57
4.2 Error Analysis for pdf of path loss distribution .................................................. 58
4.3 Simulation parameters for star-node detection simulation ..................................... 67
5.1 Simulation parameters for femto-cell analysis ..................................................... 87
6.1 Link to system mapping parameters ................................................................. 106
6.2 Shadowing parameters ...................................................................................... 107
6.3 Simulation parameters for resource partitioning simulation .................................. 110
7.1 Simulation parameters for control signalling ...................................................... 123
Acronyms and abbreviations

1G 1st Generation
2G 2nd Generation
3G 3rd Generation
3GPP 3rd Generation Partnership Project
4G 4th Generation

ACI adjacent carrier interference
ADC analogue/digital converter
AMPS Advanced Mobile Phone Service
ARQ automatic repeat request

B3G Beyond 3G
BCH broadcast channel
BS base station

CEPT Conférence européenne des administrations des postes et des télécommunications
CCI co-channel interference
CDF  cumulative distribution function

CDMA  code division multiple access

CN  core network

CSG  closed subscriber group

CTF  channel transfer function

DFT  discrete Fourier transform

DL  downlink

DL-HII  downlink high interference indicator

DL-SCH  downlink shared channel

eNB  evolved NodeB

ETSI  European Telecommunications Standards Institute

FDD  frequency division duplex

FDM  frequency division multiplex

FDMA  frequency division multiple access

FFT  fast Fourier transform

GPRS  General Packet Radio Services

GSM  Groupe Spécial Mobile

GUE  gateway UE

HDD  hybrid division duplex

HeNB  home evolved NodeB
HII  high interference indicator

ICI  inter-carrier interference

ICIC inter-cell interference coordination

ICT  information and communication technology

IMT-2000  International Mobile Telecommunications-2000

ISI  inter-symbol interference

ITU  International Telecommunication Union

LoS  line-of-sight

LTE  Long-Term Evolution

LTE-A  Long-Term Evolution Advanced

MAI  multiple access interference

MC  multi-carrier

MIMO multiple-input and multiple-output

MME  mobility management entity

MRC  maximum ratio combining

NMT  Nordic Mobile Telephony

nLoS  non-line-of-sight

OFDM  orthogonal frequency division multiplexing

OFDMA  orthogonal frequency division multiple access
PAPR  peak-to-average power ratio
PCFICH  physical control format indicator channel
PCI  physical cell identity
PDCCH  physical downlink control channel
df  probability density function
PHICH  physical hybrid-ARQ indicator channel
PLMN  public land mobile network
POTS  plain old telephone service
QPSK  quadrature phase-shift keying
RB  resource block
RE  resource element
RF  radio frequency
RMSE  root mean squared error
RNTP  relative narrowband transmit power
RSRP  reference signal received power
RTM  Radio Telefono Mobile
SC  single-carrier
SDMA  space division multiple access
S-GW  serving gateway
SINR  signal-to-interference-plus-noise ratio
SNR  signal-to-noise ratio
**Acronyms and abbreviations**

**SMS**  short message service

**TACS**  Total Access Communications System

**TDD**  time division duplex

**TDMA**  time division multiple access

**TS**  time slot

**UE**  user equipment

**UL**  uplink

**UMTS**  Universal Mobile Telecommunications System

**UL-SCH**  uplink shared channel

**UTRA**  UMTS Terrestrial Radio Access

**WCDMA**  wideband CDMA

**WINNER**  Wireless World Initiative New Radio
Nomenclature

\( \alpha \) Critical \( k \)-percentile path loss value [dB]

\( A(\theta) \) Azimuth antenna pattern [dB]

\( A_m \) Maximum possible attenuation due to sectorisation [dB]

\( a \) Antenna-dependent constant used for path loss calculation [dB]

\( b \) Path loss exponent dependent constant used for path loss calculation

\( b_c \) Number of base stations per cluster

\( C \) Capacity in general [bps]

\( C_{BS\rightarrow GUE} \) Mean capacity between the BS and a GUE [bps]

\( C_{\text{bench UE}} \) Mean end-to-end capacity in the benchmark system [bps]

\( C_{GUE\rightarrow UE} \) Mean capacity between the GUEs and their associated UEs [bps]

\( C_k \) Capacity for link \( k \) [bps]

\( c \) Speed of light [m/s]

\( c_b \) Number of channels used by each base station

\( c_r \) Number of reusable channels in system

\( c_t \) Total number of channels used by system

\( \Delta f \) OFDM subcarrier spacing [Hz]

\( \delta \) Viable communication transmission range [m]

\( D \) Distance between centres of co-channel cells [m]

\( d \) Distance between two points [m]

\( d_0 \) Close-in distance for path loss calculation [m]

\( d_{BP} \) Effective breakpoint distance [m]

\( d_{corr} \) Decorrelation distance for correlated log-normal shadowing [m]

\( \eta_{RB} \) Thermal noise over bandwidth of RB [W]
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_b$</td>
<td>Energy per information bit [Ws]</td>
</tr>
<tr>
<td>$\mathcal{F}_{\text{int}}$</td>
<td>Set of interfering femto UEs or HeNBs</td>
</tr>
<tr>
<td>$f_c$</td>
<td>Carrier frequency in general [Hz]</td>
</tr>
<tr>
<td>$f_{c_{\text{DL}}}$</td>
<td>DL band carrier frequency [Hz]</td>
</tr>
<tr>
<td>$f_{c_{\text{UL}}}$</td>
<td>UL band carrier frequency [Hz]</td>
</tr>
<tr>
<td>$f_{r}$</td>
<td>Frequency reuse factor</td>
</tr>
<tr>
<td>$\gamma_{i,k}^k$</td>
<td>SINR achieved on the $i^{th}$ subcarrier of the $k^{th}$ link</td>
</tr>
<tr>
<td>$\gamma_{\text{max}}$</td>
<td>Maximum supported SINR supported by available modulation scheme</td>
</tr>
<tr>
<td>$\gamma_{\text{min}}$</td>
<td>Minimum supported SINR supported by available modulation scheme</td>
</tr>
<tr>
<td>$G_{i,j}$</td>
<td>Link gain between receiver $i$ and transmitter $j$</td>
</tr>
<tr>
<td>$G_{\text{th}}$</td>
<td>Threshold gain associated with $I_{\text{th}}$</td>
</tr>
<tr>
<td>$\mathcal{H}_{u}$</td>
<td>Set of HeNBs in proximity of UE $u$</td>
</tr>
<tr>
<td>$</td>
<td>H_{k,i,j}^k</td>
</tr>
<tr>
<td>$</td>
<td>H_{m,n}^{i,j}</td>
</tr>
<tr>
<td>$h_{\text{eNB}}'$</td>
<td>Effective eNB antenna height [m]</td>
</tr>
<tr>
<td>$h_{\text{UE}}'$</td>
<td>Effective UE antenna height [m]</td>
</tr>
<tr>
<td>$I_{n,u}$</td>
<td>Aggregate interference experienced by UE $u$ on RB $n$ [W]</td>
</tr>
<tr>
<td>$I_{\text{th}}$</td>
<td>Interference threshold for resource partitioning [W]</td>
</tr>
<tr>
<td>$K$</td>
<td>Number of clusters in coverage area</td>
</tr>
<tr>
<td>$k$</td>
<td>Degree of a node/vertex in a graph</td>
</tr>
<tr>
<td>$\mathcal{L}$</td>
<td>Set of co-channel interferers</td>
</tr>
<tr>
<td>$\Lambda$</td>
<td>Capacity gain due to intra-hotspot communication</td>
</tr>
<tr>
<td>$L$</td>
<td>Path loss in general [dB]</td>
</tr>
<tr>
<td>$L_{\text{free}}$</td>
<td>Free space path loss between two points [dB]</td>
</tr>
<tr>
<td>$L_{\text{tw}}$</td>
<td>Wall penetration loss [dB]</td>
</tr>
<tr>
<td>$\mathcal{M}_{\text{int}}$</td>
<td>Set of interfering macro UEs or eNBs</td>
</tr>
<tr>
<td>$M$</td>
<td>Total number of edges in a graph of $n$ nodes</td>
</tr>
<tr>
<td>$M_{\text{ant}}$</td>
<td>Number of receive antennas</td>
</tr>
<tr>
<td>$\mathcal{N}$</td>
<td>Set of all available RBs</td>
</tr>
<tr>
<td>$\mathcal{N}_k$</td>
<td>Set of subcarriers allocated for link $k$</td>
</tr>
<tr>
<td>$\overline{\mathcal{N}}_i$</td>
<td>RBs that are prohibited for HeNB $i$</td>
</tr>
<tr>
<td>$\nu$</td>
<td>Attenuation factor representing implementation losses for link adaptation</td>
</tr>
<tr>
<td>$n$</td>
<td>Number of nodes in a graph</td>
</tr>
<tr>
<td>Symbol</td>
<td>Definition</td>
</tr>
<tr>
<td>-------</td>
<td>------------</td>
</tr>
<tr>
<td>$N$</td>
<td>Thermal noise [W]</td>
</tr>
<tr>
<td>$N_0$</td>
<td>Thermal noise power spectral density [W/Hz]</td>
</tr>
<tr>
<td>$N_c$</td>
<td>Number of OFDM subcarriers available</td>
</tr>
<tr>
<td>$N_{c}^k$</td>
<td>Number of OFDM subcarriers allocated to link $k$</td>
</tr>
<tr>
<td>$N_{\text{cells}}$</td>
<td>Number of macro-cells in scenario</td>
</tr>
<tr>
<td>$N_{\text{sys}}^{\text{GUE}}$</td>
<td>Number of GUEs in system</td>
</tr>
<tr>
<td>$N_{\text{RB}}$</td>
<td>Number of RBs available</td>
</tr>
<tr>
<td>$N_{\text{sys}}^{\text{UE}}$</td>
<td>Number of UEs in system</td>
</tr>
<tr>
<td>$N_{\text{avail}}^{\text{TS}}$</td>
<td>Number of available TSs</td>
</tr>
<tr>
<td>$N_{\text{BS-GUE TS}}$</td>
<td>Number of TSs allocated to the BS-GUE DL link</td>
</tr>
<tr>
<td>$N_{\text{GUE-UE TS}}$</td>
<td>Number of TSs allocated to the GUE-UE UL/DL link</td>
</tr>
<tr>
<td>$N_{\text{TS}}^k$</td>
<td>Number of TSs allocated to link $k$</td>
</tr>
<tr>
<td>$N_{\text{RB}}^{\text{prohibited}}$</td>
<td>Number of RBs prohibited for HeNB $i$</td>
</tr>
<tr>
<td>$\psi$</td>
<td>Bandwidth utilisation [bps/Hz]</td>
</tr>
<tr>
<td>$P_{\text{eNB}}$</td>
<td>eNB transmit power per RB [W]</td>
</tr>
<tr>
<td>$P_{\text{FUE}}$</td>
<td>Femto UE transmit power per RB [W]</td>
</tr>
<tr>
<td>$P_{\text{HeNB}}$</td>
<td>HeNB transmit power per RB [W]</td>
</tr>
<tr>
<td>$P_{\text{i}}^k$</td>
<td>Transmit power of transmitter $i$ on the $k^{\text{th}}$ subcarrier [W]</td>
</tr>
<tr>
<td>$P_{\text{MUE}}$</td>
<td>Macro UE transmit power per RB [W]</td>
</tr>
<tr>
<td>$p$</td>
<td>Probability of the occurrence of an edge in a random graph</td>
</tr>
<tr>
<td>$p_a$</td>
<td>Probability of the existence of an active HeNB in an apartment</td>
</tr>
<tr>
<td>$Q$</td>
<td>Co-channel reuse ratio</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Spectral efficiency in general [bps/Hz]</td>
</tr>
<tr>
<td>$\rho_{\text{bench}}$</td>
<td>Spectral efficiency in benchmark system [bps/Hz]</td>
</tr>
<tr>
<td>$\rho_{u}^n$</td>
<td>Spectral efficiency on RB $n$ for UE $u$ [bps/Hz]</td>
</tr>
<tr>
<td>$\rho_{\text{prop}}$</td>
<td>Spectral efficiency in proposed TDD underlay system [bps/Hz]</td>
</tr>
<tr>
<td>$R$</td>
<td>Information rate [bps]</td>
</tr>
<tr>
<td>$R_c$</td>
<td>Hexagonal cell major radius [m]</td>
</tr>
<tr>
<td>$R_h$</td>
<td>Hotspot radius [m]</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Standard deviation of log-normal shadowing [dB]</td>
</tr>
<tr>
<td>$\varsigma$</td>
<td>Power control balancing factor</td>
</tr>
<tr>
<td>$S$</td>
<td>Received signal power [W]</td>
</tr>
<tr>
<td>$\vartheta$</td>
<td>Average number of edges in a random graph</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>$\theta_{3dB}$</td>
<td>Angle at which half gain is achieved from central lobe [deg]</td>
</tr>
<tr>
<td>$T_d$</td>
<td>Channel delay spread [s]</td>
</tr>
<tr>
<td>$T_s$</td>
<td>Symbol duration [s]</td>
</tr>
<tr>
<td>$T^{MC}_s$</td>
<td>MC symbol duration [s]</td>
</tr>
<tr>
<td>$T^{SC}_s$</td>
<td>SC symbol duration [s]</td>
</tr>
<tr>
<td>$T_u$</td>
<td>OFDM modulation-symbol duration [s]</td>
</tr>
<tr>
<td>$t_u$</td>
<td>LTE subframe duration [s]</td>
</tr>
<tr>
<td>$U_{\text{aff}}^i$</td>
<td>Set of macro UEs exposed to strong interference from HeNB $i$</td>
</tr>
<tr>
<td>$v_u$</td>
<td>H/eNB serving UE $u$</td>
</tr>
<tr>
<td>$W$</td>
<td>Bandwidth in general [Hz]</td>
</tr>
<tr>
<td>$W_c$</td>
<td>Subcarrier bandwidth [Hz]</td>
</tr>
<tr>
<td>$W_{RB}$</td>
<td>RB bandwidth [Hz]</td>
</tr>
<tr>
<td>$\xi$</td>
<td>Zero-mean Gaussian distributed log-normal shadowing [dB]</td>
</tr>
<tr>
<td>$X_\sigma$</td>
<td>Log-normal shadowing value [dB]</td>
</tr>
<tr>
<td>$X_k$</td>
<td>Number of $k$-star-nodes in a given graph</td>
</tr>
<tr>
<td>$x(t)$</td>
<td>Basic OFDM symbol at time $t$</td>
</tr>
<tr>
<td>$Y_k$</td>
<td>Number of $K$-star-nodes in a given graph</td>
</tr>
<tr>
<td>$Y_u^n$</td>
<td>Received signal power observed by UE $u$ on RB $n$ [W]</td>
</tr>
<tr>
<td>$\zeta$</td>
<td>Path loss exponent</td>
</tr>
</tbody>
</table>
Introduction

1.1 About this Thesis

The issue of deploying high-capacity next generation wireless networks is addressed in this thesis. With the increasing uptake of so-called *smartphones* in recent times, it has been repeatedly identified that state-of-the-art cellular networks are fast being rendered incapable of consistently delivering the excessively high throughputs demanded by the Internet-savvy users of such devices [1, 2]. Furthermore, recent studies have indicated that a significant proportion of data traffic is generated indoors [3]. Yet, indoor users suffer the most because the transmissions either originate from base stations positioned outdoors and must pass through walls before reaching their destination or vice-versa. In order to circumvent these wall penetration losses, research in *femto-cells* has been rife in recent times. Femto-cells, which are low-cost base stations (BSs) having a wired (or even a wireless) backhaul to the core network (CN), are envisaged to be deployed in homes and offices in the coming years in order to bring high-speed connectivity to the vulnerable indoor users. This work primarily focuses on assessing the impact of femto-cell deployment on cellular networks and addressing the various issues associated with femto-cell deployment.
1.2 The Case for Femto-cells

No other industry has ever seen a growth as fast as that seen in the mobile telecommunications sector. This has also made the mobile phone the single most widespread information and communication technology (ICT) to date. From almost no penetration fifteen years ago, today nearly 49.5% of the population in developing nations makes use of mobile telecommunication technologies [2]. In 2002, nearly 44% of all mobile subscriptions came from the developing world (which contains a fifth of the world’s population). Within a span of five years, the proportion of mobile subscriptions originating from the developing world exploded to 64% (Fig. 1.1).

![Figure 1.1: The growth in the number of mobile subscriptions has been most significant in the developing world. Whereas in 2002, the developed world had a majority of mobile subscriptions, by 2007, this had been overtaken by the developing world.](image)

Worldwide, at the end of 2008, it was estimated that 61.1 people out of a hundred make use of mobile phones. To put that into perspective, this means that there are over four billion people making use of mobile phones today. Figs. 1.2(a) and 1.2(b) reveal that this is not a passing phenomenon either as the number of fixed telephone lines in the world is on the decline, showing that mobile phones are quickly replacing landlines as the main source of point-to-point communication [2]. Furthermore, over a fifth of the world’s population uses the Internet, as shown in Fig. 1.2(c), and as mobile communications become increasingly more capable of supporting real-time online applications, the number of mobile broadband subscriptions are expected to rise in the coming years, as demonstrated in Fig. 1.2(d) [2]. In fact, with over half of the developed world having access to the Internet, the number of mobile broadband subscriptions in the developed world has already experienced a significant surge. The International Telecommunication Union (ITU) has repeatedly highlighted the importance of broadband for development [2]. Numerous studies (for example [4]) have shown that the Internet is instrumental in the development of a nation. Many of the most effective applications that foster development
Introduction

(a) Global ICT developments (approximate).
(b) Mobile cellular growth (approximate).
(c) Internet users (approximate).
(d) Mobile broadband users (approximate).

Figure 1.2: Global ICT developments (a). Nowadays the number of mobile subscriptions exceeds the number of landline subscriptions by a factor of three. The trends in the number of mobile subscriptions (b) showing the rapid growth in the developing world. The number of internet users (c) and the rapid uptake of mobile broadband subscriptions (d).

(such as e-commerce, e-government, e-banking or simply dissemination of information) are only available through a high-speed Internet connection. However, access to fixed broadband is often difficult or simply not available in developing nations. In 2007, 19.4% of the developed world had access to fixed broadband in comparison to only 2.4% of the developing world [2]. In such cases, providing high-speed Internet access over the already established mobile network is of paramount importance.

Femto-cells, to this end, offer tremendous potential to fulfill this role successfully. From the operator’s point of view, the cost of deploying a femto-cell is much lower than the cost of deploying a dedicated BS [3]. Furthermore, depending on the manner in which a femto-cell is set up, access can be granted to either a selected set of user equipments (UEs) or to all UEs within its range. The latter method of access, in particular, is what makes femto-cells the perfect enabler for bringing Internet connectivity to areas with limited fixed line access in developing nations since one such femto-cell could potentially serve a number of users.
1.3 Contributions

Using the original time division duplex (TDD) underlay concept [5, 6], the work presented in this thesis first builds on subsequent work [7].Briefly, the TDD underlay concept cleverly exploits two components intrinsic to traditional urban cellular networks: users are usually distributed in clusters rather than uniformly and traffic is usually asymmetric in nature, \textit{i.e.}, it is heavier in one direction than the other, usually this happens to be the downlink (DL) [8]. From every cluster of users, one user is chosen to act as a wireless gateway between the rest of the users and the macro-cell BS. System-level simulations using Wireless World Initiative New Radio (WINNER) air interface parameters are performed and they indicate that there is a significant amount of capacity available within each cluster of users owing to the fact that intra-cluster transmission distances are typically very small in comparison to intra-cell distances found in state-of-the-art cellular networks and the fact that there are no wall penetration losses within indoor clusters. However, this research also highlights the fact that due to the wireless link between the gateway and the BS and the fact that the transmission distance between the evolved NodeB (eNB) and the gateway is significantly larger than that between the gateway and its served UEs, there is a bottleneck which restricts the throughput that can be delivered to the users within a cluster.

Next, some mathematical work is done in the context of \textit{ad hoc} cluster formation. In particular, the issue of path loss distribution between nodes in a randomly deployed network is addressed. The probability density function (pdf) of the distribution of path losses in such a network is derived. Using these results, a key question with regard to \textit{ad hoc} networks is answered: what is the probability that any given node in such a network can form communication links with \textit{k} other nodes? In connection with this, the concept of the \textit{star-node} is introduced and a mathematical treatment of the probabilities connected with star-nodes is shown.

Femto-cells consist of mini BSs deployed indoors. They are connected to the backbone network via a wired backhaul which means that the bottleneck identified above is rendered redundant. Obviously, in contrast to the work highlighted above, a UE does not need to serve other UEs of a cluster; a situation which can severely limit the battery life of the UE in question. These improvements are taken into account in the next stage of research, where a system-level simulation with femto-cells embedded in a cellular network is presented. The increases in system capacity with a varying number of femto-cells in the system are shown. A performance analysis of different femto-cell access methods is also performed. In particular, the limitations of \textit{closed-}
access femto-cell deployment and their impact on macro-cell performance are highlighted.

Femto-cells can be configured in many ways. One particular method of setting up a femto-cell is known as closed-access, whereby the femto-cell BS maintains a list of selected UEs (these UEs are a subset of all the UEs served by the macro-cell BS) which it grants access to. Any other UE also in the vicinity of this femto-cell must be served by the macro BS. This introduces the undesirable situation in which this UE experiences very severe DL interference from the femto-cell and, in turn, causes very severe uplink (UL) interference to it. We assume that priority lies with the macro-cell, such that nomadic macro UEs must be ensured service above femto UEs. In this light, the next phase of research focuses on mitigating the DL interference caused to macro UE in cellular networks with embedded closed-access femto-cells. A novel technique is introduced whereby the offending femto-cell must refrain from using DL resources allocated to vulnerable macro-cell UEs. Performance analysis shows that the DL capacity of such vulnerable macro UEs can significantly be improved using this method.

1.4 Thesis Layout

Chapter 2 lays the groundwork for the research presented in subsequent chapters. In this chapter, a brief overview of the history and evolution of cellular networks is presented. Next, the need for femto-cells is motivated by highlighting some of the benefits of femto-cell deployment in a traditional cellular network. This section also discusses some of the issues connected with femto-cell deployment. A few key concepts such as duplexing, frequency reuse and multiple access methods are covered since they will be used throughout the remainder of this thesis. This chapter ends by motivating the need to improve indoor coverage in future mobile systems. Finally, the femto-cell, along with all its advantages is introduced.

Chapter 3 introduces the TDD underlay concept in the context of a frequency division duplex (FDD) overlay network. The first contribution of this thesis is then presented in this chapter by showing the applicability of the TDD underlay concept to femto-cells. The basic premise of this work is based on the fact that the clustered distribution of users that is typically observed in an urban scenario is a commodity that can be exploited. From every such cluster of users, one is selected to act as a gateway between the rest of the users and the BS. It has been shown that the TDD underlay concept is particularly suited for this purpose.

The ad hoc nature of user clusters leads to the investigation of the mathematical properties
of randomly deployed networks. In Chapter 4, first the pdf of the distribution of path losses between uniformly distributed nodes in a circular area is derived. This information is then used to determine the probability of detecting so-called star-nodes in such a network. Star-nodes have the property of being within the communication range of \( k \) or more (where \( k \geq 3 \)) nodes. Star-nodes are of particular importance to ad hoc networks since their existence can determine the success of connectivity of the nodes within such a network.

The research is then taken in the direction of hierarchical orthogonal frequency division multiple access (OFDMA)-FDD cellular networks with embedded femto-cells in Chapter 5. Universal frequency reuse is assumed such that the femto and macro-cells both reuse the entire available bandwidth. This work draws two clear conclusions: the capacity of cellular networks can be boosted tremendously through femto-cell deployment and femto-cell deployment can severely affect the performance of some poorly positioned macro UEs, particularly in the DL.

Chapter 6 investigates the findings highlighted in the previous chapter in further detail. It has been identified that poorly positioned macro UEs suffer severely from DL interference from nearby femto-cells. A novel resource partitioning scheme is proposed by which such detrimental interference can be mitigated. First, a simple study highlights the effectiveness of the scheme and next, the results of a detailed Long-Term Evolution (LTE)-compliant simulation are presented.

Finally, conclusions of the above research, a discussion on the limitations in its current state and directions for future research are presented in Chapter 7.
Chapter 2

Motivation and Background

2.1 An Historical Overview: Towards LTE

Mobile communications have come a long way since the introduction of the first mobile telephone systems in the 1950s. Aside from the fact that the user equipments (UEs) were bulky and power-hungry, therefore forced to be car-borne, there were more serious problems to contend with: each geographic zone was allocated a specific frequency with the base station (BS) transmitting with a power as high as that allowed by the federal specifications. Not only did this limit the number of concurrent connections, but moving from one zone to another meant that the call would necessarily have to be dropped and then re-initiated. Clearly, these primitive services severely limited the number of active users to the number of channels assigned to a particular frequency zone. Roaming between different networks was impossible as there was no commonly agreed standard.

The well-known generational phase of mobile telecommunications started in the early 1980s, beginning with the introduction of the so-called 1st Generation (1G) of mobile telecommunications standards. The first international mobile communication system was the Nordic Mobile Telephony (NMT) system which was introduced in 1981 in the Nordic countries, Switzerland, Netherlands, Eastern Europe and Russia [9]. At around the same time, Advanced Mobile Phone Service (AMPS) systems were rolled out in the U.S.A. and Australia, Total Access Communications System (TACS) in the U.K., C-450 in West Germany, Portugal and South Africa, RC2000 in France, Radio Telefono Mobile (RTM) in Italy and several competing systems in Japan. All
these deployments were analogue in nature and therefore supported only plain old telephone service (POTS), i.e., voice with some related supplementary services. More importantly, however, was the fact that with a standardised service being offered over a large geographic area, the idea of roaming originated, such that users moving out of the area of the home operator could still be served by other operators. This feature appealed to a much larger and more comprehensive customer base. The revenue generated through new subscriptions attracted many new companies into the business.

With the foundation having been laid, focus shifted towards digitising these networks. Doing so allowed the operator to increase system capacity in order to keep up with the growing rate of new subscriptions, thereby increasing reliability (analogue networks often suffered from inconsistent quality and cross-talk between users) and the possibility to introduce services beyond just voice. Furthermore, a push was made to introduce region-wide systems encompassing many countries. In Europe, the planning for such a system began as early as 1982, when the Conférence européenne des administrations des postes et des télécommunications (CEPT) created the Groupe Spécial Mobile (GSM) to develop a standard for a mobile telephone system that could be used across Europe. In 1989, the responsibility for GSM development was transferred to the European Telecommunications Standards Institute (ETSI) and the first phase of the GSM specifications were published in 1990. Subsequently, the first GSM network was deployed by Radiolinja in Finland. These 2nd Generation (2G) time division multiple access (TDMA)-based networks, being digital in nature, were capable of providing in addition to traditional voice services, data services such as short message service (SMS) and circuit-switched data services such as e-mail. In the second half of the 1990s, packet data services such as General Packet Radio Services (GPRS) were introduced. Systems with these additions became known as 2.5G systems and despite their relatively low data rates, they began to hint at what was possible for applications over packet data in future systems. GSM, which started out as a pan-European project quickly gained so much momentum that almost all countries across the globe adopted the standard. With a worldwide audience, the stage was set for the next generation of cellular technologies, with a much tighter international cooperation than ever before.

The widespread deployment of 2G networks was accompanied by research into 3rd Generation (3G) networks during the 1990s. In fact, the International Telecommunication Union (ITU) had started work on International Mobile Telecommunications-2000 (IMT-2000), better known as 3G mobile communications in the 1980s. The number 2000 was chosen because (i) the system
was expected to be available at the start of the new millennium, (ii) it promised data rates of at least 2000 kbps and (iii) it was supposed to operate in the 2000 MHz region [10]. GSM networks could provide circuit-switched data at download speeds of up to 14.4 kbps. However, with a rapidly growing demand for multimedia applications and Internet connectivity on the handset, it was clear that future networks would need to support much higher data rates [2]. In Europe, 3G was named Universal Mobile Telecommunications System (UMTS). Simultaneously, 3G research was conducted in other parts of the world with Japan, Korea and U.S.A., all fervently working on 3G wireless communication technologies. The 3rd Generation Partnership Project (3GPP) is the standards-developing body that specifies the 3G UMTS Terrestrial Radio Access (UTRA) systems, which are the air interfaces. 3GPP is an international consortium consisting of several international standardisation bodies based in the U.S.A., Japan, China and Korea, in addition to Europe. The first 3G networks started being deployed in the early 2000s with the aim of providing a minimum data rate of 2 Mbps for stationary or quasi-stationary users and up to 348 kbps for mobile users. The technological platform upon which 3G systems were to be built was chosen as code division multiple access (CDMA), especially because research had indicated that CDMA would be able to not only support a very large bandwidth and support a large number of users (theoretically infinite), but would also be immune to interference [11]. Unfortunately, implementations of networks using CDMA technology have been unable to reproduce its theoretical benefits [12]. Another reason for the slow uptake of 3G systems is because the recommended spectrum allocation in the IMT-2000 could not be easily implemented as the requested frequency spectra were partially or fully in use in many countries, thus stifling true global roaming.

In order to keep up with user demands in terms of data rate and to increase system capacity, Long-Term Evolution Advanced (LTE-A), which is a 3GPP effort, is the latest development towards 4th Generation (4G) systems. Long-Term Evolution (LTE) gets its name from the fact that the enhancements are being designed to be competitive for the next decade. In keeping with this, the spectral efficiency targets specified in [13] are 5 bps/Hz in the downlink (DL) and 2.5 bps/Hz in the uplink (UL). For a 20 MHz bandwidth, this translates to a peak data rate of 100 Mbps and 50 Mbps in the DL and UL, respectively, easily rivalling state-of-the-art home broadband speeds. In addition to this, emphasis has also been laid on delivering acceptable cell-edge performance. Due to the proliferation of wireless services, large chunks of spectrum are difficult to procure. Bearing this, LTE-A is designed to operate in a wide range of frequency bands and size of spectrum allocations with orthogonal frequency division
multiplexing (OFDM) as the key enabling technology. Therefore, LTE-A can use spectrum allocations ranging from 1.4 to 20 MHz and addresses all frequency bands currently identified for IMT-2000 systems by the ITU including those below 1 GHz [14, 15]. Finally, 4G systems are also required to operate in both paired and unpaired spectra, depending on availability. Therefore, such systems are envisaged to work seamlessly in either the time division duplex (TDD) or frequency division duplex (FDD) mode, ensuring the implementation of multi-mode UEs and making global roaming a true possibility [14].

2.2 Overview of Concepts

2.2.1 Methods of Increasing Data Rates

As has been demonstrated in Section 2.1, cellular networks over the years have been evolving so as to support ever increasing data rates. In the same vein, one of the main targets for the evolution of 3G communication systems is to provide significantly higher end-user data rates. In order to understand how this can be achieved, the basics of channel capacity and the factors that affect it are discussed in this section.

The channel capacity as defined by Claude Shannon [16] can be expressed as

\[ C = W \log_2 \left( 1 + \frac{S}{N} \right), \] (2.1)

where \( W \) is the bandwidth of the channel, \( S \) is the received signal power and \( N \) is the white noise interacting destructively with the received signal. Therefore, the fraction \( S/N \) represents the signal-to-noise ratio (SNR). Let \( R \) denote the information rate of a particular communication link. The received signal \( S \) can be represented as \( S = E_b R \), where \( E_b \) is the received energy per information bit. Furthermore, let the noise be represented as \( N = N_0 W \), where \( N_0 \) is the constant noise power spectral density measured in W/Hz. The information rate can never exceed the channel capacity. Therefore,

\[ R \leq C = W \log_2 \left( 1 + \frac{E_b R}{N_0 W} \right). \] (2.2)

Let \( \psi = R/W \) be defined as the bandwidth utilisation. Thus
Motivation and Background

\[
\psi \leq \log_2 \left( 1 + \psi \frac{E_b}{N_0} \right). 
\]  

(2.3)

Rearranging (2.3), a lower bound on the required received energy per information bit normalised to the noise power density for a given \( \psi \) can be expressed as

\[
\frac{E_b}{N_0} \geq \min \left\{ \frac{E_b}{N_0} \right\} = \frac{2^\psi - 1}{\psi}. 
\]  

(2.4)

Fig. 2.1, plotted according to (2.4), shows the minimum required \( \frac{E_b}{N_0} \) as a function of the bandwidth utilisation. This graph shows two sections: one which is almost constant and another containing a steep slope. It is seen that when the bandwidth utilisation is significantly less than one, i.e., for information rates smaller than the utilised bandwidth, the minimum required \( \frac{E_b}{N_0} \) is relatively constant. Therefore, in this region, for a given value of \( N_0 \), any increase of information data rate implies a similar relative increase in the minimum required signal power, \( S \), at the receiver. This is known as power-limited operation. However, when the bandwidth utilisation is greater than one, the minimum required \( \frac{E_b}{N_0} \) increases rapidly with \( \psi \). This means that when the data rate is of the same order as or larger than the communication bandwidth, any further increase in the data rate, for the same bandwidth, must be accompanied by a much larger relative increase in the minimum required received signal power. This is known as bandwidth-limited operation. Therefore, from this, it becomes clear that in order to make efficient use of the available SNR, the communication bandwidth should be at least of the same order as the data rates that are to be provided.

It is clear from (2.1) that capacity is limited by the bandwidth and the SNR. Arbitrarily in-
increasing the bandwidth to meet capacity requirements is not a practical solution. One method of increasing capacity, keeping the bandwidth constant, is through the use of multiple antenna technology, i.e., multiple-input and multiple-output (MIMO) techniques. MIMO allows the exploitation of the spatial domain as a new dimension [14]. There are three main types of gain associated with MIMO: diversity gain, array gain and spatial multiplexing gain. Diversity gain uses the multiple antennas to improve the robustness of the transmission against multipath fading (discussed in the following). Array gain is the concentration of energy in one or more directions via precoding or beamforming. Finally, spatial multiplexing gain allows the transmission of multiple signal streams to a single user on multiple spatial layers created by combinations of the available antennas.

Bandwidth is a commodity that is scarce and, more importantly, extremely expensive. Furthermore, the use of wider bandwidth increases the complexity of both the transmitter and the receiver, having a direct impact on the power consumption and cost of manufacturing the equipment. In addition to this, widening the bandwidth increases corruptions of the signal during transmission. After the signal propagates through space, multiple copies of it are received at the destination via multiple paths, each with a different delay (see Fig. 2.2). This causes the signal to be spread in the time domain and this is termed as the delay spread. In the frequency domain, such a time-dispersive channel causes variations in the channel frequency response. The extent to which a channel undergoes frequency selectivity depends on the bandwidth of the transmitted signal. Wider band transmissions cause a larger amount of frequency selectivity. Frequency selective channels are known as wideband channels since the bandwidth of the signal is wider than the coherence bandwidth of the channel [17]. The amount of frequency selectivity also depends on the environment in such a way that environments with fewer obstructions or
Motivation and Background

reflectors cause less frequency selectivity. Finally, as the mobile terminal moves through the environment, due to Doppler spread, the signal will also vary in time, with more rapid variations the higher the *Doppler spread* is. Fig. 2.2 shows the variation in time and frequency of a 10 MHz channel over a 3 s window for a mobile terminal moving at 3 km/h.

Receiver-side equalisation [18] has traditionally been used to counter frequency selectivity. Satisfactory performance from equalisation has been observed for wideband CDMA (WCDMA) systems with bandwidths up to 5 MHz [19]. LTE systems are expected to operate with a wide range of bandwidths from 1.25 MHz up to 20 MHz [20]. With higher bandwidths, the complexity involved with receiver-side equalisation becomes problematic. In order to cope with the higher bandwidths, alternative approaches that combat frequency selectivity with a reasonable receiver complexity have been proposed. One method of achieving this is by making use of multi-carrier (MC) transmission, *i.e.*, transmitting a wideband signal as many narrow-band frequency-multiplexed signals. A particularly attractive form of MC is known as OFDM. OFDM has been adopted by LTE as the key enabling technology [21] and will be discussed in more detail in Section 2.2.4.3.

One of the other methods of increasing capacity is by improving the SNR. In a noise-limited scenario, in order to improve the SNR, the power of the received signal must be increased. The most obvious means of achieving this, keeping transmit power constant, is by reducing the distance between the transmitter and the receiver. A reduced transmission distance results in lesser attenuation of the desired signal due to path losses. In the context of cellular networks, this would mean reducing the cell size. In an interference-limited scenario, decreasing the cell-size also brings potential interferers closer and therefore results in an increase in interference. If the cell size is kept unchanged, this would mean that relatively high capacities can only be achieved at the cell-centre. In contrast to previous communication systems which stressed the importance of delivering high peak data rates, LTE is targeting a fairer approach by aiming to achieve significantly higher data rates over the entire cell, with a special emphasis on delivering high cell-edge throughput [20, 22].

### 2.2.2 Frequency Reuse

As mentioned in Section 2.1, the first mobile communication systems were created such that one high-power BS served a large geographic area. However, it has been pointed out that this setup was infeasible since it did not allow for roaming and, more importantly, supported a very
limited number of users [23, 24]. The *cellular* concept emerged in order to combat these issues. Each cellular BS (transmitting with a relatively lower power compared to the BSs of the first mobile systems) is allocated a group of radio channels to be used within a small geographic area, known as a *cell*. Neighbouring cells must use a different set of channels in order to limit the amount of interference experienced by the cell in question. Such a grouping of cells, with each using orthogonal sets of channels relative to its neighbours, is known as a *cluster*. A large coverage area can be created by repeating the clusters of cells, such that the system bandwidth is *reused* several times. This selection and allocation of channel groups among the BSs of a system is known as *frequency reuse* [25]. Fig. 2.3 illustrates the frequency reuse concept for clusters of size seven. While not accurately reflecting reality, the hexagonal shape of cells is generally used in order to enable an easy analysis of cellular systems. The amount of interference that is tolerable by the system determines the cluster size. The number of times a set of channels is reused within a system is directly proportional to the cluster size. Obviously, it is advantageous to maximise the reuse of a set of channels, however, it must be noted that this is limited by the amount of interference the system can tolerate. This leads to the conclusion

![Figure 2.3: An example of frequency reuse with three clusters, each consisting of seven cells. Every cell within a cluster uses a different set of channels (A-G) from its immediate neighbours. The clusters are indicated by bold outlines. Three clusters are depicted here. Cells reusing resources are spatially separated in order to reduce interference caused to one another.](image-url)
that there is a trade-off between bandwidth usage and interference. *Frequency planning* refers to the effective optimisation of this trade-off.

If $R_c$ is the radius of the cell and $D$ is the distance between the centres of co-channel cells, the ratio, $Q = D/R_c$, known as the *co-channel reuse ratio*, can be used to explore the aforementioned trade-off better. By increasing the value of $Q$, the spatial separation between co-channel cells relative to the coverage distance of a cell increases. This reduces interference by increasing isolation between co-channel cells. In contrast, a smaller value of $Q$ increases capacity at the cost of higher co-channel interference (CCI).

Let $c_r$ be the number of reusable channels in a system. These channels are shared by the various cells belonging to a cluster. Let the clusters be repeated $K$ times over the coverage area. The total number of channels, $c_t$, that are used by the system is

$$c_t = Kc_r. \quad (2.5)$$

If $c_b$ is the number of channels allocated to every BS and the number of BSs per cluster is $b_c$, then the number of channels per cluster, equivalent to the total number of reusable channels in the system, $c_r$, can be denoted as

$$c_r = b_cc_b. \quad (2.6)$$

Using (2.5) and (2.6), the total number of channels utilised by the system can be represented as

$$c_t = Kb_cc_b. \quad (2.7)$$

It is seen from (2.7) that for a constant number of BSs in the system, *i.e.*, $Kb_c$, $c_t$ can be increased if the number of channels per BS, $c_b$, is reduced. Doing this implies that the number of BSs per cluster, $b_c$, is decreased and the overall number of clusters in the system, $K$, is increased. As already mentioned, this raises the issue of the interference vs. bandwidth utilisation trade-off. Increasing the value of $c_t$ results in a desirable increase in system capacity. The important metric known as the *frequency reuse factor*, $f_r$, which denotes the fraction of channels used by each BS, is introduced as

$$f_r = \frac{1}{b_c}. \quad (2.8)$$
In LTE systems, a frequency reuse factor of one is essential in order to maximise system capacity [14]. This means that every BS is allowed to utilise the entire available system bandwidth. This results in a cell experiencing high interference on the data and control channels from its immediate neighbours. In order to avoid low cell-edge throughput due to increased interference, it is necessary to employ interference mitigation techniques such as

- Interference coordination/avoidance
- Inter-cell interference randomisation
- Frequency-domain spreading
- Power control
- Partial frequency reuse at cell-edges

The work presented in this thesis does not employ any of the above techniques despite employing a frequency reuse factor of one, since the focus is on the worst-case system-level performance analysis.

### 2.2.3 Duplexing Techniques

In any cellular system, bi-directional traffic is essential for successful communication. In this context, the two traffic directions are defined. Traffic originating from the BS and received by the UE is known as DL traffic. Conversely, UL traffic originates from the UE and terminates at the BS. The coordination of DL and UL is termed as *duplexing*. Two main duplexing techniques exist. These are introduced in the following subsections.

#### 2.2.3.1 Frequency Division Duplex

In FDD, UL operation takes place on a frequency band that is completely non-overlapping with the frequency band used for DL operation as shown in Fig. 2.4. The separation in frequency between the two bands is known as the guard frequency.

FDD offers some advantages:
Motivation and Background

Since each traffic direction operates in its own dedicated frequency band, both, UL and DL can take place simultaneously. This is particularly suited to time-critical services such as voice traffic.

Since each traffic direction operates in its own distinct frequency band, in the UL, only other concurrent UL transmissions are sources of interference. Similarly, in the DL, only other concurrent DL transmissions are sources of interference. Therefore, in FDD, UL interference experienced by any BS is caused solely by UEs and DL interference experienced by any UE is caused solely by BSs serving other cells in the system. As a result, these two types of interference are termed as other entity interference.

There are, however, some disadvantages, the most important of which are:

- For asymmetric services, such as packet-based data traffic and Internet usage, FDD is at a clear disadvantage due to the fixed frequency allocations which cannot be changed according to traffic demands.

- Since the UL and DL bands need to be sufficiently separated so as not to interfere with one another, precious frequency spectrum is often wasted in FDD. This spectrum can be used for other applications, however, care must be taken to make sure that these do not cause any interference to the FDD system.

- Due to simultaneous UL and DL operation on different frequency bands, each transceiving unit requires two sets of radio frequency (RF) frontends (receiver, transmitter and RF filter) in addition to a duplexer, thus increasing costs of production.

- Future mobile communication systems such as LTE systems are envisaged to operate with varying bandwidth requirements (between 1.4 and 20 MHz [14, 15]). Due to the
proliferation of wireless services nowadays, finding unoccupied paired spectra of the required bandwidth is extremely difficult, if not impossible. Even though many countries (such as the U.K. and the U.S.A.) are making efforts to free up significant amounts of spectrum by switching off analogue TV transmissions, this remains an important issue for pure FDD systems.

2.2.3.2 Time Division Duplex

As the name suggests, in TDD, DL and UL operations can be toggled in time as per traffic demands. For either traffic direction, the frequency of operation remains the same. In comparison to FDD, TDD does not require a guard frequency band. However, when making a switch between reception and transmission of traffic, a guard time interval is required. When switching from UL to DL, the guard interval is the time required by the hardware to switch from transmission to reception. When switching from DL to UL, since all UEs in a cell are synchronised in time, this guard interval must account for the round trip delay of the signal between the cell-centre and cell-edge. As a result, this guard interval is longer than the guard interval required for the switch between UL and DL [26]. In TDD, there are various time slots (TSs) such that every TS is dedicated to either UL or DL traffic. Depending on the TS allocation, every time a transition between UL and DL is made, a guard time interval is required. This is depicted in Fig. 2.5.

![Figure 2.5](image)

**Figure 2.5:** In TDD, UL and DL operations occur on the frequency band but are toggled in time. In this example, there are two switching points between UL and DL operation. Clearly, the traffic demands here are in favour of the DL. The two guard time intervals are shown when switching traffic direction.

The most important advantages of TDD are:

- TDD is very flexible in adapting to cell-specific traffic asymmetry demands. As a re-
sult of this, each cell has complete control in the allocation of UL and DL resources. TDD is very important in the context of current (and future) wireless networks which are packet-based and characterised by high peak-to-average traffic ratios [27–29]. It is very important that such systems are able to dynamically adapt to changing traffic demands.

- Since the same frequency band is used in both traffic directions, in the case of power control, there is no need for channel information feedback as the channel remains the same regardless of the direction of traffic. This important property of TDD systems is known as channel reciprocity [28].

- Since UL and DL share the same frequency in TDD, a transceiver requires only one set of oscillators and filters. This drives down the hardware costs.

- TDD is particularly well suited to deploying multi-hop relaying in a network at low additional costs since each relay station requires only a simple transceiver [30].

The most important disadvantages of TDD can be listed as:

- Compared to FDD, there are more sources of interference in TDD. As expected, this is same entity interference, i.e., UE → UE and BS → BS interference. Since BSs are generally located in exposed areas, due to the high probability of line-of-sight (LoS) between themselves, they cause high interference to each other. In TDD, when a UE in one cell is in the UL mode and another UE in another cell is in the DL mode, same entity interference occurs. This can also occur in the absence of synchronisation between BSs when the starts of TSs occur independently of each other in different cells. Recent work [31] aims to address this issue by introducing a virtual switching point to the TDD system.

- Inter-operator interference occurs in TDD systems because operators can be given adjacent frequency bands and since they need to synchronise their networks to a common reference and adopt the same asymmetry, the flexibility that TDD generally affords is lost [32].

- Since the guard intervals depend on the round trip delay between the cell-centre and cell-edge, for large cell sizes, significant efficiency losses can occur with TDD implementations. As a result of this, TDD is well suited for small cell sizes but not for large ones [28, 29].
While the FDD duplexing technique is used in the work presented in Chapters 3, 5 and 6, the work shown in Chapter 3 employs a hybrid FDD-TDD duplexing method.

2.2.4 Multiple Access Techniques

The manner by which several UEs are coordinated in order to access the resources meant to be shared within a cell is termed as \textit{multiple access}. The three most basic multiple access techniques are TDMA, frequency division multiple access (FDMA) and CDMA. However, hybrids of these methods also exist, \textit{e.g.}, orthogonal frequency division multiple access (OFDMA). As mentioned before, OFDMA is gaining considerable interest within the context of future wireless systems, especially LTE [9, 14]. This technique is therefore discussed in more detail than the others in the coming subsections.

2.2.4.1 TDMA and FDMA

When using TDMA, users requesting access to resources are multiplexed in time such that at any time instant, one and only one user is granted access to the whole bandwidth [17]. Therefore, each user is allocated the entire bandwidth at non-overlapping time instants from other users. This is shown in Fig. 2.6. TDMA can be combined with either of the two duplexing methods already explained in the previous section, \textit{i.e.}, TDD or FDD. When combined with TDD, \textit{i.e.}, TDMA-TDD, a user requesting access to resources is allocated the entire bandwidth for the required number of TSs in the UL part of the transmission and for the appropriate number of TSs in the DL part of the transmission. As expected, in TDMA-FDD operation, a user is allocated UL and DL resources simultaneously in its own dedicated TS.

As the name suggests, when using FDMA, users requesting access to resources are multiplexed in frequency such that a user is granted access to a fraction of the frequency spectrum for the
Motivation and Background

entire time duration [17]. In this way, each user is allocated a dedicated, non-overlapping part of the frequency spectrum for the entire time duration. This is shown in Fig. 2.7. Similar to

![Figure 2.7](image)

**Figure 2.7**: In FDMA operation, users are granted access to non-overlapping parts of the frequency spectrum for the entire time duration.

TDMA, FDMA operation can be combined with either duplexing technique. In FDMA-TDD, users requesting access to resources are granted UL and DL resources during different time instants but in their own dedicated frequency band. In contrast, in FDMA-FDD operation, a user is granted UL and DL resources at the same time but in different frequency bands.

### 2.2.4.2 CDMA

CDMA differs from TDMA and FDMA in that it permits multiple access over the entire frequency bandwidth for the entire time duration to all users. The separation between users is achieved in the *code domain* by assigning a different (or orthogonal) code to each user [17, 28]. Every transmitted signal is multiplied by a relatively large bandwidth spreading signal that is user-unique such that this signal is seen as noise by all other users. Due to this, CDMA is known as a spread spectrum technique. This is depicted in Fig. 2.8. Each additional user increases the overall noise level observed by the others. As a result, CDMA systems are said to be interference-limited [33]. For this reason, power control is of paramount importance for proper CDMA operation since the received power level needs to be constant for all users. In connection with this, the near-far effect is identified as a problem for CDMA, where, due to lack of perfect power control, the received power from an interfering link is higher than that from the desired link, leading to a very low SNR value. However, if implemented properly, CDMA allows for a frequency reuse factor of one and is the main multiple access method used in 3G technologies such as UMTS [34].

21
Motivation and Background

In CDMA operation, users are granted access to all frequency resources for the entire time duration. Orthogonality between users is achieved by assigning a unique code to each user.

2.2.4.3 OFDMA

OFDMA is a multiple access technique that is built on OFDM, which itself is a special case of frequency division multiplex (FDM) [35]. The concept of OFDM dates back to the 1960s [36, 37], however it was only with the invention of the discrete Fourier transform (DFT) and the fast Fourier transform (FFT) that OFDM systems were able to be implemented in practice [38, 39]. OFDM and OFDMA fall into the class of MC transmission techniques, as opposed to single-carrier (SC) transmission techniques. The choice of an appropriate multiple access technique is especially critical to achieving good performance of mobile wireless systems because mobile radio channels are typically frequency-dispersive and time-variant, as explained. MC transmission, as will be demonstrated, is particularly well-suited to combat these channel imperfections.

In MC transmission, a fast serial data stream is transformed into several slower parallel data streams, *i.e.*, the channel bandwidth is divided into a number of parallel subchannels. Ideally, the bandwidth of each subchannel is such that it is non-frequency-selective and can therefore be said to have a spectrally-flat gain [14]. This is especially beneficial in bringing down receiver hardware costs and complexity. In OFDM, the narrowband, spectrally-flat subchannels into which the frequency-selective wideband channel is divided are overlapping but orthogonal to one another. This obviates the need to separate the narrowband channels using guard intervals as is the case for FDM. This leads to significant savings in spectrum and Fig. 2.9 depicts these savings compared against classical SC transmission and FDM. Using frequency-flat narrowband subchannels in MC transmissions, *i.e.*, OFDM, in a cellular mobile radio system was first proposed in 1985 [40]. Since then, with advances in digital signal processing, after a lot of research and development, the technology has found its way into the implementation of LTE systems. OFDM has the special advantages that the receiver can be of low-complexity...
and more importantly, is well-suited to be flexible enough to operate in different channel bandwidths according to the availability of spectrum.

Serially transmitted, high data-rate streams typically have a symbol duration, $T_s$, which is much smaller than the channel delay spread, $T_d$. This is the source of inter-symbol interference (ISI) [17] and can only be mitigated by means of equalisation, the complexity of which grows with the square of the channel impulse response length [18]. In OFDM, the bandwidth is divided into several narrow subcarriers and the symbol duration is longer than the SC case. This is shown in Fig. 2.10.

The OFDM modulator consists of $N_c$ complex modulators, where each modulator corresponds
Motivation and Background

to one OFDM subcarrier. The subcarriers are sinc-shaped in the frequency domain. Due to this, they are orthogonal to one another. This is shown in Fig. 2.11. The subcarriers are separated by $\Delta f = 1/T_u$, where $T_u$ is the per-subcarrier modulation-symbol time. In complex baseband notation, during the time interval $mT_u \leq t < (m + 1)T_u$, the basic OFDM symbol, $x(t)$, can be expressed as

$$x(t) = \sum_{k=0}^{N_c-1} x_k(t) = \sum_{k=0}^{N_c-1} a_k^{(m)} e^{j2\pi k\Delta ft},$$  

(2.9)

where $x_k(t)$ is the $k$th modulated subcarrier with frequency $f_k = k\Delta f$ and $a_k^{(m)}$ is the general complex, modulation symbol applied to the $k$th subcarrier during the $m$th OFDM symbol interval. During each OFDM symbol interval, $N_c$ modulation symbols are transmitted in parallel. These modulation symbols can be from any modulation alphabet such as quadrature phase-shift keying (QPSK), 16QAM, 64QAM, etc. The modulation process is depicted in Fig. 2.12. 

OFDM gets its name from the fact that any two modulated subcarriers are mutually orthogonal over the time interval $mT_u \leq t < (m + 1)T_u$, i.e.,

$$\int_{mT_u}^{(m+1)T_u} x_{k1}(t)x_{k2}^*(t)dt = \int_{mT_u}^{(m+1)T_u} a_{k1}^{(m)} a_{k2}^{(m)*} e^{j2\pi k1\Delta ft} e^{-j2\pi k2\Delta ft} dt = 0.$$

(2.10)

The basic principle of OFDM demodulation is shown in Fig. 2.13. The demodulator consists of a bank of correlators, one for each subcarrier. In the ideal case, due to orthogonality, two OFDM subcarriers do not induce any interference to one another after demodulation. This is the case despite the fact that their spectra overlap as illustrated in Fig. 2.9 due to the specific frequency domain structure and the choice of the subcarrier spacing, $\Delta f$, as shown in Fig. 2.11.

![Subcarrier spacing in OFDM. These seven subcarriers are orthogonal to one another in the frequency domain.](image)

Figure 2.11: Subcarrier spacing in OFDM. These seven subcarriers are orthogonal to one another in the frequency domain.
Motivation and Background

Figure 2.12: Basic principle of OFDM modulation. A serial stream is converted to parallel, modulated onto orthogonal narrowband subcarriers and then added.

However, any corruption of the frequency domain structure or the OFDM subcarriers will result in the loss of orthogonality between the subcarriers, unlike MC transmission, where a physical frequency guard band creates the orthogonality between subcarriers. In order to make the OFDM signal truly robust to radio channel frequency selectivity and combat the loss of orthogonality between subcarriers, a cyclic prefix is inserted at the time of modulation. The reader is urged to refer to [38, 41] for more theoretical information on OFDM and to [9, 14] for the practical implementation of the technology in LTE systems.

Figure 2.13: In OFDM demodulation, a bank of correlators separate the transmitted stream into the components of each subcarrier.

The physical resource in case of OFDM transmission is often illustrated as a time-frequency grid. This is shown in Fig. 2.14, where each column corresponds to one OFDM symbol and
Motivation and Background

Figure 2.14: The typical OFDMA time-frequency grid. At each TS, the various resources in the frequency domain can be allocated to multiple users.

each row corresponds to one OFDM subcarrier. This time-frequency grid structure will be revisited in Chapter 5 when discussing the LTE frame structure and resource allocation.

The discussion, until now, has assumed that a single user receives data on all subcarriers at any given time. However, like FDM, OFDM can easily be adapted to behave as a multiple access technique. This is called as OFDMA where the subcarriers are distributed among different users at the same time so that multiple users can be scheduled to receive or send data simultaneously.

Usually, the subcarriers are allocated in contiguous groups in order to reduce overhead required to signal which subcarriers have been allocated to which user. However, a distributed user multiplexing is also possible where the subcarriers need not be allocated in contiguous groups.

OFDMA for mobile communications was first proposed in [42] based on MC FDMA in which each user is assigned a set of randomly selected subchannels.

In [43–45], it is shown that, for a system with multiple users, significantly more information can be transmitted across a fading channel than a non-fading channel for the same average signal power at the receiver. This is known as multiuser diversity. The major benefit of OFDMA is that it enables OFDM transmission to benefit from multiuser diversity. One way of achieving this is by allocating each subcarrier to the user experiencing the best fading conditions on that subcarrier, as shown in Fig. 2.15. If all the resources were to be allocated to just one user, due to the multiple fades that the user experiences over the whole bandwidth, the spectrum would be underutilised.

The most important advantages of OFDMA can be listed as:

- OFDMA is very scalable [28], which means that it can be deployed for systems with
Figure 2.15: The benefit of multiuser diversity is demonstrated here. The different users experience different fading conditions over the bandwidth. Each frequency resource is allocated to the user that experiences the best channel conditions on that resource.

widely varying bandwidths. This can be achieved as long as the frequency separation between the subcarriers and the symbol duration remain the same for all the systems. While the frequency and time granularities remain the same, in order to compensate for the change in bandwidth, the FFT size needs to be adjusted. This implies that the air interface remains unchanged for different deployment scenarios, which is very important in the context of global roaming.

- OFDMA-enabled systems are capable of turning the multi-path effect, which is usually considered as a detriment to wireless systems, into an advantage. Due to the propagation environment, multiple copies of the signal are received, resulting in a delay spread. Usually, this causes ISI, which is the smearing (in the time domain) of one transmitted signal into the subsequent one. Since the OFDM symbol duration is typically longer than the channel delay spread, ISI is significantly suppressed in OFDMA systems. Multiuser diversity is then used to maximise capacity through smart resource allocation.

The main drawbacks of OFDMA are:

- In order to avoid ISI, the cyclic prefix must be chosen with a length that is longer than
Motivation and Background

the longest channel impulse response to be supported [14]. Since the cyclic prefix carries redundant information, the longer it is, the more overhead the system has.

- The orthogonality of OFDM relies on the condition that both the transmitter and the receiver operate with exactly the same frequency reference [14]. If this cannot be ensured, perfect orthogonality between the subcarriers is lost and inter-carrier interference (ICI) results. The mismatch between the reference frequency at the receiver and transmitter usually arises from a mismatch between the reference frequency of the local oscillators. Since emphasis is laid on developing low-cost mobile terminals, the frequency drifts are usually more severe at the UE.

- High peak-to-average power ratios (PAPRs) occur because the OFDM signal is an aggregation of sinusoids. From the central limit theorem [46], the time domain OFDM symbol may be approximated as a Gaussian waveform. Due to this, the amplitude variations of the OFDM modulated signal can be very high. There are several methods proposed to combat PAPR. These generally fall into the categories of clipping, filtering [47–49] and coding techniques [50, 51].

Finally, since LTE is designed to satisfy demands in relation to spectrum flexibility and deployment, it is designed to operate in either TDD or FDD mode [14,52]. Therefore, LTE has support for OFDMA-FDD and OFDMA-TDD modes of operation. In the presence of paired radio spectrum, i.e., FDD operation, two grids as depicted in Fig. 2.14 are available, one each for DL and UL. For TDD operation, in the presence of unpaired spectrum, the basic time-frequency grid remains the same, but only a subset of the resources are used for UL and the rest for DL with appropriate guard period. In TDD operation, channel reciprocity between UL and DL assists in scheduling [14,28]. This is not the case with FDD operation. However, TDD has the disadvantage of poor time synchronisation, which can lead to adjacent carrier interference (ACI). The systems discussed in chapters 3, 5 and 6 operate in the OFDMA-FDD mode.

2.3 Calculating Capacity

In the following chapters, one of the main metrics used to evaluate the performance of a system is capacity. In light of this, the capacity calculation in an OFDMA system and issues related to it are discussed in this section.
If a cellular network exclusively offers 2G voice services, the capacity is measured as the number of duplex voice channels that can simultaneously be occupied in the system [17]. In such a network, each user requires only one duplex voice channel to sustain a satisfactory communication link. Therefore the number of supported channels is equivalent to the number of users than can be served simultaneously. This equivalence is possible because the system offers only one service: voice. Due to this, the data rate per user, across the system, is the same. The majority of 2G networks are based on either TDMA/FDMA or CDMA techniques. Networks of the former variety are known to be bandwidth-limited, i.e., the capacity depends on the number of available channels and networks of the latter type are known to be interference-limited since the frequency reuse factor $f_r = 1$ and any addition of users to the system increases the interference in it.

The number of users that can be served simultaneously in a TDMA/FDMA system is fixed and determined by the system bandwidth and cluster size. When the cluster size is small, the bandwidth is reused more often within the system. In such a setup, the number of users served per cell is not likely to reach the maximum possible limit due to increased CCI from other cells in nearby clusters. As a result, the capacity of such a system is interference-dependent and is known as soft capacity [53]. Conversely, if the cluster sizes are large, the number of available channels per cell is lower than the previous case. This results in lower CCI, which means that in such a system, the user is more likely to be denied service due to non-availability of channels. Therefore, this is known as hard capacity. The capacity in CDMA systems is similar to the soft capacity discussed for TDMA/FDMA systems. In CDMA systems, the cluster size is one. Orthogonality between users is achieved by assigning a unique spreading code to each user. However, despite this, CCI is still a limiting factor in these systems since the transmission of each user is seen as interference by other users. Therefore, the capacity of such systems is limited by the tolerable interference level in the system.

In 3G and future networks, voice is not the only service that is offered. In addition to voice services, such networks also offer data services. In such systems, the users do not all have the same data rate requirements. Different numbers of channels are allocated to different users, depending on their demands. Furthermore, in OFDMA systems, each subcarrier can be allocated a different data rate depending on the propagation conditions. Therefore, in this case, it does not make sense defining capacity as the number of occupied channels or the number of users served. As a result, a more useful metric in this case is the total system data rate or the average
user data rate. As seen in (2.1), capacity depends on the bandwidth. Therefore, in order to facilitate a comparison between systems of differing bandwidths, oftentimes, the spectral efficiency is used as an evaluation metric. Spectral efficiency, \( \rho \), measured in bps/Hz, is calculated as

\[
\rho = \log_2 \left( 1 + \frac{S}{N} \right), \tag{2.11}
\]

such that it is the capacity normalised over the bandwidth. In other words, spectral efficiency is defined as the ratio of the data rate to the bandwidth.

Both, (2.1) and (2.11), are dependent on the SNR. However, in a practical system, the signal-to-interference-plus-noise ratio (SINR) is used such that the interference in the system is also accounted for. In a conventional OFDMA system, the SINR achieved at a receiver \( u \), \( \gamma_u \), is calculated as

\[
\gamma_u = \frac{1}{|N_u|} \sum_{k \in N_u} \frac{P^{v_u}_k |H^{u,v_u}_k|^2 G_{u,v_u}}{\sum_{l \in L} P^{l}_k |H^{u,l}_k|^2 G_{u,l} + N}, \tag{2.12}
\]

where \( v_u \) is the intended transmitter, \( L \) is the set of co-channel interferers, \( N_u \) is the set of subcarriers allocated to receiver \( u \) with cardinality \( |N_u| = N^u_c \), such that \( 0 \leq N^v_c \leq N_c \), with \( N_c \) being the number of OFDMA subcarriers available in the system, \( P^{v_u}_k \) is the transmit power on the \( k \)th subcarrier of the transmitter \( v_u \), \( |H^{u,v_u}_k|^2 \) is the channel transfer function on the \( k \)th subcarrier between receiver \( u \) and transmitter \( v_u \), \( G_{x,y} \), in general, is the link gain between a receiver \( x \) and a transmitter \( y \) and finally, \( N \) is the thermal noise in the system.

As is seen, (2.12) only iterates over the set of subcarriers allocated to user \( u \), i.e., \( N_u \). In other words, this equation only takes into account CCI. This assumes that the system is perfectly synchronised and that there is no interference leaking from other subcarriers. However, as has already been discussed in Section 2.2.4.3, OFDMA systems are not immune to frequency offsets due to Doppler shifts and synchronisation errors. Therefore, in OFDMA systems, multiple access interference (MAI) is also a source of interference, and as the name suggests, originates from the cell of interest. In order to account for this additional source of interference, (2.12) needs to be further modified. The reader is directed to [54,55] for a detailed explanation of how this is done.
2.4 Motivation

Previously, as cellular networks gained popularity, attention was given to increasing network capacity by allowing a larger number of users to communicate simultaneously. Section 2.2.1 discusses various theoretical methods of boosting the capacity of a wireless link. Many proposals exist to increase system capacity by increasing the number of simultaneous transmissions, such as cell splitting, cell sectorisation, zone division, power control \[10, 17\], etc.

In a cellular network, due to the non-uniform distribution of users \[56\], hotspot regions often develop. These are small geographic areas with a dense population of users demanding channel access. To counter this problem, the cell splitting concept has been proposed \[57–59\]. Cell splitting is the process of dividing a congested cell into smaller cells, each having its own BS, with a reduced antenna height and transmit power. A different layer of cells which are smaller in size (micro-cells) is overlaid on top of the existing large-size macro-cells. These micro-cells serve users with lower mobility rates while the macro-cells serve the highly mobile users. Indoor, pedestrian-speed users are served by even smaller pico-cells, each with their own indoor BS. The introduction of such a layered cell architecture increases the reuse of the available number of channels in the system and enables better frequency planning such that the entire network does not have to cater to the worst-case demand. This flexibility in frequency management leads to an enhancement in capacity.

Cell splitting effectively increases capacity by decreasing the cell radius, \(R_c\), but keeping the value of the co-channel reuse ratio, \(Q\), fixed. This increases the number of channels per unit area. Another method of increasing capacity is by decreasing the value of \(Q\) as explained in Section 2.2.2. This is achievable through cell sectorisation \[60, 61\]. Sectorisation is a space division multiple access (SDMA) technique in which directional antennas (as opposed to omnidirectional ones) are made use of. These antennas direct their transmissions to a certain part of the cell such that the same channels can be reused within the other parts of the cell. Usually, the hexagonal cell is partitioned into three 120° sectors or six 60° sectors. In order to further reduce CCI, the antennas can also be down-tilted. Sectorisation leads to an increase in the frequency reuse factor, \(f_r\), by reducing the number of cells within a cluster, \(b_c\). Sectorisation also leads to a decrease in the value of \(Q\) since the cell radius remains unchanged but the distance between co-channel cells, \(D\), is decreased.

As already mentioned, cellular networks suffer from the near-far problem if transmit powers
are fixed regardless of the location of the UE. The signal from a UE close to the BS is received with a very high power. This signal dominates the adjacent channel transmissions received from UEs lying far away from the BS, thus causing high interference to those transmissions. Power control is therefore used to mitigate this problem. The BS issues power control commands to the UEs of its cell such that all transmissions are received with a constant power.

In recent times, with the advent of smartphones [62], mobile network providers have begun to experience an unprecedented surge in demand for higher data rates. The mobile handset is nowadays considered as an information hub which integrates various services such as audio, video, storage, television, computing and commerce [63]. Studies on the origination of traffic in wireless networks have begun to show that more than 50% of all voice calls and over 70% of all data traffic originates from indoor areas [3]. While voice services are engineered to tolerate a low data-rate and poor signal qualities, this is not the case for data services, where the signal quality must be good in order to maintain a reasonable data-rate. It has been identified that cellular networks suffer from coverage holes, especially in indoor areas. This is because the signal undergoes heavy attenuation when passing through walls. For a UE placed indoors in a traditional cellular network, this signal attenuation, attributed to wall penetration loss, is unavoidable. Since a high percentage of traffic is seen to originate indoors, future networks are preparing to improve indoor coverage for their users. Over the years, several proposals have been made to alleviate this problem. In [64], the authors propose that a building be divided into several small cells, such that each cell is served by its own dedicated antenna, with each antenna operating on non-overlapping frequency bands. In [65], the authors propose a cell splitting approach wherein micro-cells are embedded within the macro-cell, each serving a different class of user. However, the different types of cells employ different multiple access technologies (CDMA in one and TDMA in the other). The work presented in [66] makes use of repeaters installed by the operator to improve indoor coverage. Finally, in [67], the authors propose the deployment of operator-installed fill-in sites in order to solve the coverage hole problem. These fill-in sites operate either on the same frequency as the core network or operate on a different bandwidth. While all of these proposals help provide indoor coverage, there are several issues preventing their widespread deployment:

- All of these proposals assume the addition of operator-installed infrastructure to the cellular network in all indoor areas where the signal quality is unacceptable.
- Some of the proposals assume system operation using different technologies simultane-
From the operator’s point-of-view, it is not very cost-effective to install additional BSs in the network, given the high cost of the deployment and maintenance of each BS [3]. All of the proposals covered here require careful network planning, which is also costly and time-consuming. Furthermore, in order to function indoors in the systems proposed in [64, 65, 67], a dual-mode UE is required. The work in [64] proposes that each inter-building cell use a fraction of the total available bandwidth. Doing this reduces the bandwidth available to UEs lying indoors and severely curtails the data-rate that is actually achievable. Finally, since the responsibility of the installation of infrastructure is always borne by the operator, none of these proposals allow the end-user to fill a coverage hole on their own if the signal quality is unacceptable. It will be shown in the following that femto-cells address all these issues and bring benefits to the core network (CN) while still alleviating the problem of poor reception indoors.

Clearly, the simplest and most effective method of increasing capacity is by reducing the transmission distance. Doing this not only improves the signal quality, but also enables more spatial reuse [68]. This is because, with a reduction of transmission distance, the transmission powers can be lowered. This enables a higher number of co-channel links to co-exist in the same area without causing detrimental interference to one another. The gains from reducing transmission distances can be put into perspective. Over the last 105 years, wireless capacity has doubled every 30 months. Since 1957, this translates to a million-fold increase. If these gains were to be broken down, wider spectrum is responsible for a 25-fold increase, dividing the spectrum into smaller slices (cellular concept, reuse, etc.) has resulted in a 5-fold increase, better modulation schemes account for another 5-fold increase. However, the remaining 1600-fold increase in capacity is attributed to smaller cell sizes, and, therefore, reduced transmission distances [3]. As has been mentioned before, the problem with continuing the reduction in cell size is the associated high cost of the installation of infrastructure. Femto-cells deviate from the norm of infrastructure being installed by the operator. Femto-cells are basically home BSs which are inexpensive, short-range, low-power devices to be installed indoors by the end-users themselves. Hereafter, using LTE terminology, in the context of femto-cells, the home BS will be known as the home evolved NodeB (HeNB). The HeNB communicates with the CN via the end-user’s broadband connection [3, 69]. The collection of the HeNB and the UEs that it serves will be known as the femto-cell. Finally, henceforth, the outdoor BS will be known as the evolved NodeB (eNB). Fig. 2.16 depicts an example of a HeNB.
Femto-cells offer several important advantages:

- Since femto-cells are deployed indoors, the transmission distances are significantly reduced. This results in higher achieved SINRs which translates to a boost in capacity.

- Due to their indoor deployment, the UEs placed indoors need not communicate with the outdoor eNB. As a result, the detrimental wall penetration losses are completely circumvented [3, 69], leading to higher achievable capacities.

- The reduction in transmission distance coupled with the avoidance of wall penetration losses means that the transmit powers can be significantly reduced while still achieving very high SINRs within the femto-cell [3]. This ties in very closely with recent research initiatives known as green radio which aim to minimise the energy consumption of cellular networks [70–73].

- The cost of deploying femto-cells is borne by both the operator and the end-user.

- Since indoor users are envisaged to be served by femto-cells, the capital expenditure in deploying new serving macro eNBs for the operator is greatly reduced [69].

- The HeNB is never needlessly deployed; end-users will only invest in it if they feel that their capacity demands are not being met.

- In contrast to all the earlier proposals [64–67] which aim to improve coverage indoors, femto-cells have the advantage that the HeNBs operate using the same air interface.
and technology as the macro-cell eNB. Therefore, there is no need for multi-mode UEs. Thus, the concept of femto-cells is already very standards-compliant and only minor modifications may be required in order to accommodate specific HeNB requirements [74].

- Since indoor users are served by deployed HeNBs, these users are offloaded from the macro-cell. Therefore, the eNB can devote the freed resources to better serve the macro-cell users who typically experience poor service, e.g., cell-edge users [75]. This ties in very well with the aim of delivering satisfactory cell-edge performance in LTE.

Fig. 2.17 depicts a macro-cell with embedded femto-cells. The indoor femto UEs are offloaded completely from the macro-cell. Therefore, the eNB is able to allocate all its resources among only the macro UEs and the HeNBs serve the femto UEs.

![Diagram of a macro-cell with embedded femto-cells.](image)

**Figure 2.17:** Two femto-cells, each containing three femto UEs, embedded within a macro-cell containing two macro UEs. The HeNBs are connected to the backbone network via a wired link and serve the femto UEs. The macro UEs are served by the outdoor eNB.

To conclude, several trends have been identified that must be catered for by future networks [63, 76]. It will be shown that femto-cells satisfy all the demands placed by these trends:

- **Support for advanced and wideband multimedia services.** It is clear that with the high achievable capacities due to deployed HeNBs, networks with embedded femto-cells will certainly be able to deploy such services, especially in indoor areas where they are expected to be demanded most. Furthermore, the freed resources will allow the macro-cell
to improve service to nomadic outdoor users as well.

- **Extended coverage area.** As mentioned, femto-cells extend cellular network coverage to indoor areas, where previously it has not been possible to provide satisfactory coverage.

- **Low delay.** Since the femto-cell has a wired backhaul to the core network, it is expected that they will not undergo very latent transmissions.

- **High data rate.** It will be shown that this is indeed achievable with femto-cell deployment.

- In [76], it is envisaged that future mobile communications systems will integrate existing and newly developed wireless systems. Therefore UEs in such systems will have to be able to support multiple technologies. However, it has been pointed out that in order for this to be possible, the UE will need to adopt a software radio search [77]. However, implementing this still remains an issue due to the need for multiple hardware to work with different frequency bands. Furthermore, current analogue/digital converters (ADCs) are still not fast enough to allow for satisfactory performance. In contrast to this, femto-cells elegantly address this issue by working with the same air interface as the underlying macro-cell network. Due to this, the use of legacy UEs is possible and there is no need for a cognitive radio approach or wireless system discoveries [78].

- In [76], the problem of vertical handover between various wireless systems has been identified for envisaged 4G system solutions. This problem does not exist with femto-cells, which operate with LTE air interfaces and technologies.

### 2.5 Summary

This chapter has served to summarise the key concepts in relation to cellular communications. To begin with, an evolution of cellular networks over the last fifty years has been presented in order to put the LTE initiatives into perspective. Next, attention is diverted to presenting the key concepts that will be required for the remainder of this thesis. In connection with this, first the concept of Shannon capacity is introduced. This section also revises methods by which capacity on a wireless link can be increased and introduces various issues related with this, *e.g.*, channel fading, bandwidth limitations, etc. Various duplexing and multiple access techniques are then introduced. Much attention is devoted to OFDMA due to its importance to LTE. Finally, this
chapter ends by covering state-of-the-art techniques that have been proposed to improve indoor cellular service and their shortfalls. This sets the foundation to introduce femto-cells in this context and to motivate why they offer a viable and sustainable complement to current cellular networks.
Chapter 3

The TDD Underlay Concept

3.1 Overview

Numerous studies, e.g., [56, 79, 80], have shown that geographic and demographic factors significantly influence the distribution of users in a cellular network. It is incorrect to assume that users in a cellular network are distributed uniformly. This is especially true in urban or suburban settings. In [79], a practical deployment of a base station (BS) in an urban setting is considered such that it is surrounded on one side by a shopping mall, a motor highway on another side and a complex of residential homes on the third side. Clearly, the traffic expected at this BS is a function of the angle of arrival. Heavy traffic is generated from the densely populated mall. These users are characterised by pedestrian speeds. Traffic originating from the highway is characterised by short call durations and high mobility, sometimes in excess of 100 km/h. Finally, as pointed out in Section 2.4, the traffic originating from the residential complex is expected to be less voice-centric and more data-centric and these users are expected to be even less mobile than the first set of users. From the discussion in Section 2.4, it is clear that the femto-cell concept is designed to cater to this last group of users [3]. However, the deployment of femto-cells should be as seamless as possible so as not to segregate groups of users by forcing them to invest in multi-mode user equipments (UEs). In this context, the femto-cell must operate on an air interface that is compatible with the already established macro-cell network.

This chapter presents a spectrum-sharing approach [81], which exploits a clustered distribution of users as would be expected in a typical home with several communicating devices or in
The TDD Underlay Concept

public places such as airports, malls, etc. Such clusters of users is henceforth termed as a hotspot. From each hotspot, a UE, known as the gateway UE (GUE), acts as a relay between the other UEs of the associated hotspot and the macro-cell BS located outdoors. The system makes use of a frequency division duplex (FDD) overlay architecture for communication between the outdoor BS and the GUE. Traffic is assumed to be asymmetric in favour of downlink (DL) as is evident from current trends in user traffic demands [29]. The unused resources in the uplink (UL) band are then used for communication within the hotspot using a time division duplex (TDD) underlay. In this way, a femto-cell is dynamically established without the requirement for any additional infrastructure to be installed. Furthermore, since the UEs of the hotspot operate on the same FDD bands as those used in the macro-cell, they need not support multiple air interfaces. Therefore, legacy UEs are capable of operating in such a system. This model is compared against one in which the same user distribution is assumed but the GUE concept is not made use of, i.e., a pure FDD system in which all UEs communicate with the BS. Based on the results, it has been shown that the proposed enhancements lead to a significant increase in system spectral efficiency through the use of intra-hotspot communication, which is not possible in the benchmark system. For the sake of discussion, one major drawback of FDD, i.e., its inability to cope with asymmetric traffic (as explained in Chapter 2) is very well suited to support this proposed TDD underlay system. If the system employed a TDD overlay system, the asymmetric traffic demand would be met due to the flexibility of TDD. Furthermore, it would not be possible to have a FDD underlay in this case due to the lack of available bandwidth. On the other hand, if the TDD overlay ratio between UL and DL were fixed such that such a system shows the same inflexibility to asymmetry as an FDD system, employing a TDD underlay would also pose problems. Such a system would experience large delays, similar to ad hoc networks.

3.2 Introduction

Due to the poor spectrum utilisation in current wireless networks, a system in which unused resources are exploited is presented as a step towards future wireless network solutions which are envisaged to be characterised by the lack of frequency planning [82]. Dynamic, self-organising and spectrum-sharing networks using femto-cellular structures are considered as improvements to the current wireless networks, which do not efficiently utilise the available bandwidth [7,83]. Ad hoc solutions to cellular networks are becoming more popular. Many proposals that add
an *ad hoc* component to traditional cellular networks have been made. We consider a few of these [84–86] here. All these proposals either require additional infrastructure to be installed in the system or require complex computations in order to satisfy a suitable routing algorithm. In [84], a hybrid *ad hoc* and cellular system is proposed, whereby a traditional cellular system switches to an *ad hoc* one as per the demands within the cell. The two modes operate on different air interfaces and would therefore require multi-mode UEs for proper operation. The proposal in [85] calls for the installation of *ad hoc* relaying stations to relay traffic from one cell to another dynamically. This proposal has the disadvantages that the operator would need to bear the costs of the planning and installation of the relaying stations and the system would suffer from increased signalling overhead. Finally, the proposal in [86] also calls for the installation of additional routers in the network. These routers introduce cell splitting such that the number of channels available per unit area increases. Smart routing algorithms help reduce the traffic load on the system, at the cost of increased overhead. Again, the operator would need to bear the cost of installing the routers and the additional complexity could pose a potential battery-drainage problem.

Next generation wireless networks face challenges in the form of a highly increased number of users, increased traffic generated by each user and traffic asymmetry in the DL. Duplexing and resource allocation are two of the critical issues in the design of next generation systems. An air interface for next generation systems must be efficient and flexible in the utilisation of spectrum and must be able to dynamically allocate resources and exploit multiuser diversity. The hybrid division duplex (HDD) architecture [87] aims to combine the advantages of FDD and TDD schemes to increase the flexibility and efficiency of a mobile communication network. Cell partitioning ensures that nomadic users are provided with high data-rates and asymmetric service through TDD, and high-speed users are given reliable service using FDD. However cell partitioning/sectoring does not solve the detrimental BS-BS and same entity interference which cellular TDD systems are afflicted with. Thus, an ideal solution is one that does not explicitly make use of cell partitioning and that is not computationally complex.

The work presented in [88,89] introduces a TDD component to a traditional code division multiple access (CDMA) cellular system operating primarily in the FDD mode, such that the same air interface is maintained, regardless of the mode of operation, FDD or TDD. Pico-cells, each of radius significantly smaller than the macro-cell, are embedded in the macro-cellular network and operate in the TDD mode. The TDD pico-cells can operate in either the DL or UL FDD.
The TDD Underlay Concept

bands. This concept is refined in [7] where the clustered distribution of users in a wideband CDMA (WCDMA) system is employed in such a way that among each cluster, one user relays information between the outdoor macro-cell BS and the rest of the indoor users. In [5, 6], the same concept is used in a UMTS Terrestrial Radio Access (UTRA)-FDD system. The TDD underlay component is deployed in the underused UL FDD band. A performance evaluation is carried out under the assumption of uniform user distribution. Since recently, the focus of research has shifted to high bandwidth, 3rd Generation (3G) orthogonal frequency division multiple access (OFDMA)-FDD systems, the work presented in this chapter [81] applies the TDD underlay concept to an OFDMA-based Wireless World Initiative New Radio (WINNER) system. Like [7], a clustered distribution of users is assumed and a two-hop communication link between the BS and the clustered users is developed using a TDD underlay.

FDD, in the classical sense (one frequency band for UL traffic and another for DL), does not effectively support channel asymmetry, as emphasised in Section 2.2.3.1. TDD, on the other hand, as discussed, is very well suited to support asymmetry since time resources can be distributed as per the asymmetry demands. Asymmetry in favour of DL results in an under-usage of the FDD UL band [6]. The idea presented in this chapter introduces an FDD-TDD switching point in the underused FDD band after which TDD is used to carry intra-hotspot load. Thus, the FDD and TDD modes are combined in a soft manner.

Let a transmission slot be defined by a certain time duration and frequency bandwidth. A transmission slot can be considered as the basic building block of a duplex communication system. A series of alternating transmission slots (one transmission slot for UL and the next for DL) at different time instances but at the same frequency results in a pure TDD system. Two clumps of simultaneous transmission slots in opposing directions, one at a particular frequency and the other clump at a different frequency result in a pure FDD system. Introducing an FDD-TDD switching point in one of the frequency bands results in an FDD system before the switching point, a TDD system after the switching point and a simplex/broadcast transmission system in the other FDD band after the switching point. Fig. 3.1 makes this concept clearer. This, then, presents an efficient and elegant method of dealing with asymmetric traffic demands of users.

There is an increasing amount of research devoted to 3G home BSs [90] which are envisaged to reduce the load on macro-cell BSs and improve quality of service to indoor users. The usefulness of this scheme to femto-cell research is apparent due to the fact that no additional
The TDD Underlay Concept

Home networks are characterised by inter-communicating devices. A traditional FDD cellular system is incapable of supporting *ad hoc* communication between the entities of a hotspot since all communication must be directed via the BS. The introduction of the TDD mode in the lesser used band enables *ad hoc* communication to take place within the hotspot without over-burdening the BS.

### 3.2.1 System Setup

#### 3.2.1.1 The Gateway UE

 Practically, for the hotspot to be formed, the UEs need to be aware of one another. One UE from each hotspot is selected as a GUE which relays traffic between the rest of the hotspot users and the BS (see Fig. 3.2). One method of doing this is by making use of the receiver-initiated, time-multiplexed busy tone concept as described in [91], *i.e.*, if the busy tone received by the GUE of a hotspot from a UE is above a pre-defined threshold, the UE belongs to that hotspot.

Introducing an additional hop in the system reduces the number of entities communicating with the BS, which leaves more resources for allocation per GUE. Also, since transmission distances are reduced, higher signal-to-interference-plus-noise ratios (SINRs) are available within the hotspot, leading to increased data-rates (especially within the hotspot) through the use of higher
The TDD Underlay Concept

Figure 3.2: Part of a cell showing one hotspot. The GUE acts as a relay between the macro-cell BS and the other UEs in the hotspot. The entire DL band is used for BS→GUE communication. Half the UL band is used for GUE→BS communication, whereas the rest of the UL band is dedicated to intra-hotspot communication in the UL and DL.

3.2.1.2 Frame Structure

Due to trends in user traffic requirements, it is assumed that all traffic in the system is asymmetric in favour of DL. Therefore, the proposed frame structure allows for channel asymmetry in favour of DL. The unused resources in the FDD UL band are used for intra-hotspot communication in the TDD mode. This is depicted in Fig. 3.2.

The frame structure is as shown in Fig. 3.3. A frame consists of two chunks (a chunk is the basic time-frequency unit for resource allocation), each of which consist of 12 orthogonal frequency division multiplexing (OFDM) symbols and 8 subcarriers. Since each chunk occupies a bandwidth of 312.5 kHz, the entire 50 MHz bandwidth (in UL and DL, each) can accommodate 160 chunks (512 subcarriers) with a subcarrier spacing of 39.0625 kHz. However, only 144 are available for use as the available bandwidth is 45 MHz (the rest being used up for guard bands) [92].

The entire DL band is dedicated to BS→GUE communication. In the UL band, in each frame, the first time slot (TS), with 144 chunks in the frequency domain is reserved for GUE→BS communication and the second TS (again with 144 chunks) can either be used for GUE→UE order modulation schemes.
or UE→GUE communication. Therefore, half the UL band is used for macro-cell UL communication and the other half is used for intra-hotspot UL/DL communication.

For the benchmark system, the same frame structure is used but without the TDD underlay. Therefore, the entire DL band is used for BS→UE communication and the entire UL band is used for UE→BS communication, resulting in a pure FDD system. In this case, the system does not provide support for asymmetric traffic and communication takes place over one hop, where all UEs communicate with the BS.

### 3.2.1.3 Path Loss Model and Log-Normal Shadowing

For path loss calculations, the WINNER path loss models are used [93]. Scenario C3 (metropol, bad urban macro-cell) is used for the macro-cell and scenario B3 (indoor hotspot) is used for the hotspot. In both cases, the non-line-of-sight (nLoS) equations are used in order to provide for the worst case scenario. The path loss models are of the form

\[
L[\text{dB}] = A \log_{10}(d[\text{m}]) + B + C \log_{10}\left(\frac{f_c[\text{GHz}]}{5}\right) + \zeta,
\]

where \(A\), \(B\) and \(C\) are constants depending on the model used, \(f_c\) is the centre frequency depending on which band is being considered (this information is shown in Table 3.1) and \(\zeta\) is a normally distributed random variable with zero mean representing the log-normal shadowing component. For the B3 path loss model, \(A = 37.8\), \(B = 36.5\), \(C = 23\) and standard deviation of the shadowing component \(\sigma = 4\) dB. For the C3 path loss model, \(A = 35.74\), \(B = 42.61\), \(C = 20\)
\[ C = 23 \] and standard deviation of the shadowing component \( \sigma = 6 \text{ dB} \). It is ensured that the path loss between any two points does not fall below the free-space path loss which is calculated using

\[
L_{\text{free}}[\text{dB}] = 20 \log_{10}(d[\text{m}]) + 46.6 + 20 \log_{10} \left( \frac{f_c[\text{GHz}]}{5} \right).
\]

In order to mimic realistic shadowing, a correlated log-normal fading model is implemented. Due to the slow fading process versus distance, adjacent fading values are correlated. The correlation in shadowing between two points separated by a distance \( d \), \( R(d) \), is given by

\[
R(d) = \exp \left( -\frac{d}{d_{\text{corr}}} \ln 2 \right),
\]

where \( d_{\text{corr}} \) is the decorrelation distance and it represents the distance beyond which there is no correlation in shadowing [94].

### 3.2.1.4 Interference and SINR

The 144 available OFDM chunks are distributed equally among the GUEs present in a macro-cell (for UL and DL). The system does not make use of power control. Instead, each entity transmits with a fixed power, whose values are obtained from [92].

Four interference scenarios exist: GUE→BS, BS→GUE, GUE→UE and UE→GUE. Same entity interference does not exist because the system is synchronised in time (crossed-slots do not exist). UEs of different hotspots also do not interfere with one another because at any given time instant, all active UEs are either transmitting or receiving.

Both, co-channel interference (CCI) and multiple access interference (MAI) are considered, where CCI represents the other-cell interference and MAI represents the own-cell interference. CCI denotes the interference caused on a chunk by other users in other-cells using the same chunk. MAI represents the interference on a chunk from neighbouring chunks allocated to other users in the same cell. For the duration of the simulation, for simplicity, since the focus is on performance evaluation, the channel is assumed to be static in time. However, frequency selective channels are simulated using Doppler shifts due to user mobility. MAI is not considered in the DL, \( i.e. \), BS→GUE, since this is a point-to-multipoint transmission and therefore perfect synchronisation between subcarriers is assumed in this direction.

MAI represents own cell interference and is modelled as the leakage from other subcarriers onto
The TDD Underlay Concept

the set of subcarriers used by that particular entity. CCI, as introduced in Chapter 2 represents other cell interference toward which all the subcarriers in the system contribute. Both, MAI and CCI, are calculated as shown in [54].

3.2.2 Simulation Model

The cellular scenario of interest used in the simulation consists of two-tiers, i.e., 19 tessellated hexagonal cells. Each cell contains an omnidirectional BS at its centre. In order to mitigate the well-known cell-boundary effect, whereby the interference at the edge of the simulation scenario is less than that at the centre of it, a dummy four-tier system is generated such that the simulation scenario is surrounded by two additional tiers consisting of the same hotspot density per macro-cell. The interfering effects of the entities in these tiers are also taken into account when calculating SINRs, thus ensuring that all users experience approximately the same amount of interference in the system. However, statistics used in the presentation of the results are only taken from the first two tiers.

The hotspots themselves are uniformly distributed in the cellular scenario. The clustered distribution of users is simulated by uniformly distributing users within the circular hotspots. It is assumed that for the duration of the simulation, the GUE is idle, i.e., it does not receive or transmit any of its own data.

Every hotspot is assumed to contain five UEs, one of which, chosen at random, becomes the GUE (see Fig. 3.4). One simulation snapshot is run for the duration of 8 frames such that every UE of a hotspot is allocated 1 TS for UL and another for DL. In the TDD part of each UL frame, every GUE communicates (either in the UL or the DL) with one UE from the hotspot. Thus, over the duration of the snapshot, there is duplex communication between the GUE and every UE in the hotspot. It is assumed that the UEs are stationary for the duration of the snapshot since the distance covered by a UE moving at pedestrian speeds during the snapshot (considering 3 km/h mobility, this is approximately 0.4 cm) is much less than the decorrelation distance, \(d_{\text{corr}}\), (see Table 3.1) of the path loss model. The distribution of users is randomised for every snapshot as are the log-normal shadowing maps.

The parameters used in the simulation are summarised in Table 3.1 and are obtained from [92, 93, 95]. A best-effort system is simulated, i.e., full-buffer transmissions are assumed and capacities are calculated based on the achieved SINRs.
Figure 3.4: One realisation of the clustered distribution for 100 hotspots, each consisting of 4 UEs and a GUE, uniformly distributed in a 2-tier scenario. The closeup shows 3 hotspots with their respective selected GUEs marked by crosses. The circles surrounding the GUE and UEs (of radius 25 m) show the area within which the UEs of a hotspot can be distributed. The labelled circles at the centre of each cell show the locations of the BSs.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation duration</td>
<td>5.5269 ms (8 frames)</td>
</tr>
<tr>
<td>Cell radius</td>
<td>577 m</td>
</tr>
<tr>
<td>Hotspot radius</td>
<td>25 m</td>
</tr>
<tr>
<td>UEs per hotspot</td>
<td>5 (including 1 GUE)</td>
</tr>
<tr>
<td>Mean user mobility</td>
<td>3 km/h</td>
</tr>
<tr>
<td>Frequency offset</td>
<td>0% to 2%</td>
</tr>
<tr>
<td>Centre frequency in UL band, $f_{c}^{UL}$</td>
<td>3.7 GHz</td>
</tr>
<tr>
<td>Centre frequency in DL band, $f_{c}^{DL}$</td>
<td>3.95 GHz</td>
</tr>
<tr>
<td>Total BS transmit power (DL)</td>
<td>50.77 dBm</td>
</tr>
<tr>
<td>Total GUE transmit power (UL)</td>
<td>24 dBm</td>
</tr>
<tr>
<td>Total UE/GUE transmit power (intra-hotspot UL/DL)</td>
<td>21 dBm</td>
</tr>
<tr>
<td>Total UE transmit power (benchmark system UL)</td>
<td>24 dBm</td>
</tr>
<tr>
<td>Antenna elevation gain</td>
<td>14 dBi</td>
</tr>
<tr>
<td>Decorrelation distance</td>
<td>3 m (B3), 50 m (C3)</td>
</tr>
</tbody>
</table>

Table 3.1: Simulation parameters.
3.2.3 Performance Metrics

In order to evaluate the performance of the system employing the TDD underlay concept, three metrics are made use of in the analysis: capacity, gain due to intra-hotspot communication and normalised spectral efficiency.

The capacity (per frame) achieved on a link $k$ between two entities is calculated as

$$C_k = \frac{N_k^{TS}}{N_{TS}^{avail}} W_c \sum_{i=1}^{N_c} \log_2 \left( 1 + \frac{\gamma^k_i}{\gamma_{b,i}} \right),$$  

(3.4)

where $W_c$ is the subcarrier bandwidth, $N_k^{TS}$ represents the number of subcarriers allocated for link $k$, $\gamma^k_i$ is the SINR achieved on the $i^{th}$ subcarrier of the $k^{th}$ link, $N_{TS}^{k}$ represents the number of TSs allocated to link $k$ and $TS_{avail}$ is the total number of TSs used in the simulation.

The capacity gain due to intra-hotspot communication is defined as the ratio of the capacity between GUEs and their associated UEs to the capacity achieved between the BSs and the same UEs in the benchmark system. This gain, $\Lambda$, is calculated as

$$\Lambda = \frac{C_{GUE \rightarrow UE}}{C_{BS \rightarrow UE}^{\text{bench}}},$$

(3.5)

where $C_{GUE \rightarrow UE}$ is the mean capacity between the GUEs and their associated UEs and $C_{BS \rightarrow UE}^{\text{bench}}$ is the mean end-to-end capacity in the benchmark system.

The normalised system spectral efficiency is defined as the system spectral efficiency normalised by the number of cells and subcarriers available. For the benchmark, this spectral efficiency, $\rho_{\text{bench}}$, is calculated as

$$\rho_{\text{bench}} = \frac{\sum_{j=1}^{N_{sys}} \sum_{i=1}^{N_j} \log_2 \left( 1 + \frac{\gamma_{b,i}^j}{\gamma_{b,i}^j} \right)}{N_c N_{cells}},$$

(3.6)

where $N_{sys}^{UE}$ is the number of UEs in the system, $N_c$ is the total number of available subcarriers in the system, $\gamma_{b,i}^j$ is the achieved SINR in the benchmark system on the $i^{th}$ subcarrier of the $j^{th}$ link and $N_{cells}$ is the number of cells in the system.

In the proposed system, the system spectral efficiency is the sum of the spectral efficiencies
achieved on the BS-GUE link and the GUE-UE link. This is calculated as

\[
\rho_{\text{prop}} = \frac{N_{\text{BS}} - GUE \sum_{l=1}^{N_{l}} \sum_{k=1}^{N_{l}} \log_2 \left( 1 + \gamma_{lBG,k} \right)}{N_{c} \times N_{\text{cells}}},
\]

\[+ \frac{N_{GUE} - UE \sum_{n=1}^{N_{n}} \sum_{m=1}^{N_{n}} \log_2 \left( 1 + \gamma_{nGU,m} \right)}{N_{c} \times N_{\text{cells}}}, \quad (3.7)\]

where \(\gamma_{lBG,k}\) is the achieved SINR on the \(l^{th}\) subcarrier of the \(k^{th}\) BS-GUE link, \(\gamma_{nGU,m}\) is the achieved SINR on the \(n^{th}\) subcarrier of the \(m^{th}\) GUE-UE link, \(N_{\text{sys}}\) is the number of GUEs in the system, \(N_{\text{TS}}^{\text{BS-GUE}}\) is the number of TSs allocated to any BS-GUE link for the simulation (this is 16, all the available TSs in the DL and 8 in the UL) and \(N_{\text{TS}}^{GUE-UE}\) is the number of TSs allocated for GUE-UE communication, which is 1 in either UL or the DL directions.

### 3.2.4 Results

Fig. 3.5 shows the capacities achieved on average for a GUE-UE pair. At any time instant,

![Figure 3.5](image)

**Figure 3.5:** Mean achieved UL/DL hotspot capacity between GUEs and their associated UEs. As the number of hotspots is increased, higher interference leads to reduced capacities.

only one entity in every hotspot is active. All GUEs and UEs transmit with the same fixed power. Since the UEs within a hotspot are geographically concentrated, they undergo similar shadowing on average, which leads to the interference being very similar across TSs. As a result, due to this and channel reciprocity, the UL and DL capacities show nearly identical trends. As the number of hotspots is increased, due to increased CCI, the capacities decrease. It can clearly be seen that despite all hotspots interfering with one another, very high intra-
hotspot capacities are still achieved, even at a very high hotspot density. These high capacities are capable of satisfying the high data demands from indoor users.

Fig. 3.6 shows the capacity gain, $\Lambda$, due to intra-hotspot communication as described by (3.5). It is seen that the capacity gain increases as the number of hotspots in the system is increased.

![Graph showing capacity gain vs number of hotspots]

**Figure 3.6:** Gain in capacity through the use of intra-hotspot communication.

This is because as the hotspot density is increased, due to very high intra-hotspot SINRs, the capacity between GUEs and their UEs does not decrease as fast as the capacity between the BSs and UEs in the benchmark system. In the benchmark system, the available macro-cell chunks in the frequency domain must be divided among all the UEs, whereas for the proposed system, the available chunks in the macro-cell only need to be divided among the GUEs. Due to this, as the hotspot density increases, the gain through GUE allocation becomes more apparent. Furthermore, it is seen that the gain in UL is higher than that in the DL. This is because the UL capacity in the benchmark system is affected by MAI, which is not the case in the DL. This causes the UL capacity in the benchmark system to be lower than the DL capacity, which translates to the capacity gain being higher in UL. The difference between the UL and DL gains reduces as the number of hotspots is increased because the difference between the UL and DL capacities in the benchmark system grows smaller with an increasing user density.

Finally, Fig. 3.7 shows the system spectral efficiencies in the proposed and benchmark systems as described in (3.6) and (3.7). It is clearly seen that the proposed and benchmark systems display opposing trends. In the benchmark system, the spectral efficiency decreases with increasing number of hotspots in the system. This is due to the fact the interference is increased.
with an increasing user density which causes the SINRs of the subcarriers to decrease, which eventually leads to a decrease in system spectral efficiency. The TDD underlay system, through intra-hotspot communication, results in an increase in system spectral efficiency because in this case, the spectral efficiency is the sum of spectral efficiencies on the BS-GUE hop and the GUE-UE hop. The SINRs on the GUE-UE link are much higher compared to the BS-GUE link (due to shorter transmission distances) and the entire bandwidth is used within a hotspot. Therefore, an increase in the number of hotspots in the system results in an increase in the system spectral efficiency.

### 3.3 Summary

This initial study presents a method of introducing a TDD component to an FDD system, thereby enabling *ad hoc* communication to take place between the entities of a hotspot without over-burdening the BS. *Ad hoc* communication between devices in close vicinity of one another is an envisaged characteristic of so-called home networks or femto-cells. Results show that this type of intra-hotspot communication can be supported through the use of the TDD underlay concept without adding any additional infrastructure to a cellular system. However, it is also apparent through these results that a clear shortcoming has been identified by introducing an additional wireless hop in a network containing clustered distributions of users. This shortcoming appears in the form of a severe capacity bottleneck on the BS-GUE hop. This is shown
in Fig. 3.8, where it is seen that whereas the GUE→UE link enjoys high capacities regardless of the hotspot density, this is not the case on the longer GUE→BS link. Therefore, although high capacities are achievable between the entities of a hotspot, this cannot be sustained by the BS-GUE link. Therefore, it is clear that deploying a femto-cell with a radio frequency (RF) backhaul to the core network (CN) as briefly proposed in [3] does not deliver the envisaged data-rates to the indoor users. In the absence of intra-hotspot communication, the highest capacity that can be achieved within the hotspot is given as $\min(C_{\text{GUE→UE}}, C_{\text{BS→GUE}})$, i.e., the capacity of a two-hop link is, at best, equivalent to the lowest capacity of the two hops. In this context, in almost all cases, $C_{\text{GUE→UE}} > C_{\text{BS→GUE}}$ since the average distance between the GUE and its associated UEs is shorter than the average distance between a macro-cell BS and a GUE, leading to higher SINRs on the former link. The only way to address this issue is to significantly increase the capacity of the BS-GUE link. However, given the constraint that the air interface, bandwidth, etc. must remain the same to allow for legacy UE operation, the only way of achieving this is to revert to a wired BS-GUE link. This then, takes the research into the realm of classical femto-cells as introduced in Chapter 2. Femto-cells, in which a wired link exists between the home BS and the CN are extensively discussed in Chapters 5 and 6.

Finally, it must be mentioned that although this proposed system does not require the addition of infrastructure or dual mode UEs, it does still incur an increase in delay in comparison to a traditional FDD system. This is because the UEs only communicate in half of the UL subframe and are idle for the other half. Furthermore since the GUE needs to schedule the other UEs of a hotspot, it might undergo excessive battery and processing drainage.
In this work, the GUE is chosen at random. However, in a practical implementation of the system, the GUE should be chosen such that it has a low path loss to the macro-cell BS and additionally, has good communication links with the rest of the UEs in the hotspot. The following chapter deals with the latter, i.e., ad hoc operation within hotspots. First, the probability density function (pdf) of path loss distribution between uniformly distributed users in a circular hotspot is derived. This result is then used to derive the probability that a hotspot of a certain radius contains one or more GUEs by defining the GUE in graph theoretic terms.
A Mathematical Treatment of Hotspots

4.1 Overview

In the previous chapter, we have dealt with non-uniform user distributions in cellular networks, such that users in urban scenarios are typically found to occur grouped together in hotspots. However, it is assumed that within hotspots, the users are distributed uniformly [96]. To recap, in Chapter 3, from each hotspot, one user equipment (UE), known as the gateway UE (GUE), was chosen at random to act as a relay between the outdoor base station (BS) and the rest of the indoor UEs. It is useful to know whether a given hotspot does indeed contain a GUE that is capable of sustaining communication links with the rest of the UEs in the hotspot. In connection with this, the issue of the existence of GUEs within a hotspot is approached probabilistically in this chapter. In order to achieve this goal, the first step is to derive the probability density function (pdf) of path loss distribution between the nodes of such a network [97]. Next, treating the network as a graph, using these results and random graph theory, the probability that a graph contains a GUE for a given path loss threshold is derived [98]. This is then extended to detect various types of GUEs, depending on the definition and finally, the probability of a graph containing several GUEs is derived.

The derivation of the pdf of path loss distribution between uniformly distributed nodes in a circular graph is treated in Section 4.2. The results presented in Section 4.2.3 are useful in their own right since they eliminate the need for time-consuming system-level simulations as will be shown. Section 4.3 then relates the GUE to a star-node before employing random graph theory
to determine the probability of detecting one or more star-nodes in from a graph containing \( n \) nodes. Finally, Section 4.4 summarises the benefits of the research documented in this chapter.

### 4.2 Path Loss Distribution within a Hotspot

#### 4.2.1 Background

A network of \( n \) transceiving units can be considered as a graph where each of the \( n \) UEs can be considered to be a node/vertex. An edge between two nodes, in graph theoretic terms, would denote a wireless link between the UEs represented by those nodes. In the following, we do not consider the entire network, but concentrate only on the hotspot. When simulating such a hotspot, the UEs are usually assumed to be distributed uniformly in space. Path losses between nodes in a simulated network are generally calculated by determining the distance between every pair of nodes and applying a suitable path loss model as a function of this distance (power of distance with an environment-specific path loss exponent) and adding a random component to represent the log-normal shadowing. A network with \( n \) nodes consists of \( \frac{n(n-1)}{2} \) path loss values, \( i.e. \), the number of edges that exist in a graph containing \( n \) nodes. In order to generate statistically significant results for system-level simulations, Monte Carlo simulations must be performed where the nodes are randomly distributed at the start of every run. This is a time-consuming operation which need not be carried out if the distribution of path losses between the nodes is known \( a \ priori \). The pdf of the path loss between the centre of a circle and a node distributed uniformly within the circle is derived in this section. Monte Carlo simulations show a perfect match with the theory derived.

System-level computer simulations of wireless, mobile networks are commonplace in current research in the wireless communications field. Users are oftentimes uniformly distributed in hexagonal cells in a system simulation. In order to find the SINR (signal-to-interference-and-noise ratio) on any link, path loss information must be known between the two communicating entities as well as the entity in question and all other potential interfering entities. Various empirically obtained path loss models exist which simulate varying propagation environments as shown in [93, 99–101]. In [102], the authors derive the pdf of the distance between two nodes within communication range of one another (based on the path loss between them). This is then extended to calculating the number of communicable nodes in the vicinity of the node in question. However, an extensive literature search has revealed that no work has been done
to analytically model the distribution of path losses between uniformly distributed nodes in a network (irrespective of whether they can sustain communication between one another or not). Therefore, this issue is addressed here.

Calculating the path loss between the nodes in a cellular system is usually done by actually distributing the nodes uniformly, calculating the distances between them and applying an appropriate path loss model to these distances. This must be repeated many times in order to get a statistically significant result. This operation is computationally expensive and simulation runtimes can be drastically reduced if this step could be skipped. In order to do so, knowledge of the distribution of path losses between uniformly distributed nodes is essential.

In this section, the pdf of the distribution of path losses between the centre of a circle and uniformly distributed nodes within it is mathematically derived. This novel derivation can then be used to find the distribution of a whole class of path loss models. A circular scenario is preferred over a hexagonal one because the derivation of the aforementioned pdf is straightforward for the circular case. However, it is also shown that the theory derived for a circular scenario agrees with the simulations for the hexagonal case very closely and is therefore a very good approximation.

### 4.2.2 Path Loss Distribution for Uniformly Distributed Users in a Circle

Path loss is generally represented as some power of distance, $\zeta$, plus a random variation about this power law due to shadowing [99]. Beyond some close-in distance $d_0$, the path loss (in dB) can be written as

$$ L = a + 10\zeta \log_{10}(d/d_0) + \xi; \quad d \geq d_0, \quad (4.1) $$

where $a$ is an intercept which is the free-space path loss at distance $d_0$, $d$ is the distance between the two points and $\xi$, the shadow fading variation about the linear relationship in the log domain, is a zero-mean, normally distributed random variable with standard deviation $\sigma$. For the sake of convenience, in (4.1), we make the substitutions $b = 10\gamma$ and $X = d/d_0$. Thus, the path loss between two points separated by $X d_0$ meters is written as

$$ L = a + b \log_{10}(X) + \xi. \quad (4.2) $$

For a hotspot of radius $R_h$, having uniform node distribution, it is known that the pdf of the
distance of any point from the centre, \( x \), is \([103]\)

\[
f_X(x) = \frac{2x}{R_h^2}, \quad x \in [0, R_h]. \tag{4.3}
\]

The angular distribution is uniform in \([0, 2\pi]\).

Using (4.2) and (4.3), the pdf of \( L \) is found to be

\[
f_L(\ell) = \frac{(\ln 10)}{bR_h^2} \exp \left\{ \frac{2b(\ln 10)(\ell - a) + 2\sigma^2(\ln 10)^2}{b^2} \right\} \left\{ 1 - \text{erf}(D) \right\}; \quad \forall \ell, \tag{4.4}
\]

where

\[
D = \frac{\ell - a - b - b^2 \log_{10}(R_h + 2\sigma^2(\ln 10))}{\sqrt{2b\sigma}} \quad \text{and} \quad \text{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt.
\]

The full derivation can be found in Appendix A.

4.2.3 Results

In this section, the match between theory and simulations is investigated for varying circle radii and standard deviations of the log-normal shadowing component. The path loss model specified in [94] is made use of. The values of the simulation parameters are listed in Table 4.1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Path loss parameter, ( a )</td>
<td>37 dB</td>
</tr>
<tr>
<td>Path loss parameter, ( b )</td>
<td>30</td>
</tr>
<tr>
<td>Radius, ( R_h )</td>
<td>50 &amp; 100 m</td>
</tr>
<tr>
<td>Log-normal shadowing standard deviation, ( \sigma )</td>
<td>6 &amp; 12 dB</td>
</tr>
</tbody>
</table>

Table 4.1: Simulation parameters.

theory derived in Section 4.2.2 is tested against simulations performed for uniformly distributed nodes in hexagons having the same major radii as the circles. This is done so as to demonstrate the practicality of the derived theory in the context of system-level cellular network simulations.

A Monte Carlo simulation is run by uniformly distributing 100,000 nodes in a circle or hexagon of the specified radius and then calculating the distance between the centre and each point. The histogram of these distances is then compared against theory. The results of the simulation are depicted in Fig. 4.1. The match between the pdfs obtained through simulations and those derived in Section 4.2.2 for varying scenario radii and log-normal shadowing standard deviation.
values is seen in Fig. 4.1(a). A perfect match between theory and simulation is seen in all cases. Furthermore, it is observed that the theory for uniformly distributed nodes in a circle very closely approximates the case when the nodes are uniformly distributed in a hexagon having the same major radius as the circle. As expected, the pdf for the hexagonal case displays a consistent shift (of approximately 1 dB) to the left. This is expected since the major radius of the hexagon is the same as the radius of the circle, causing the hexagon to fit inside the circle. Therefore, in contrast to the circular case, there are a few areas where nodes cannot exist in the hexagonal case, which causes the shift. The situation would be reversed if the minor radius of the hexagon were made equal to the radius of the circle. Fig. 4.1(b) shows the cumulative distribution functions (CDFs) associated with the pdfs depicted in Fig. 4.1(a).

An error analysis using the root mean squared error (RMSE) is performed and the results highlight the extremely close match between simulation and theory even for the hexagonal case. Table 4.2 shows the RMSE for the different radius and standard deviation values and for the circular and hexagonal cases.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>RMSE (circular)</th>
<th>RMSE (hexagonal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R = 50 \text{ m}, \sigma = 6 \text{ dB}$</td>
<td>$2.9929 \times 10^{-4} \text{ dB}$</td>
<td>$0.004 \text{ dB}$</td>
</tr>
<tr>
<td>$R = 50 \text{ m}, \sigma = 12 \text{ dB}$</td>
<td>$2.3683 \times 10^{-4} \text{ dB}$</td>
<td>$0.0016 \text{ dB}$</td>
</tr>
<tr>
<td>$R = 100 \text{ m}, \sigma = 6 \text{ dB}$</td>
<td>$2.8676 \times 10^{-4} \text{ dB}$</td>
<td>$0.0032 \text{ dB}$</td>
</tr>
<tr>
<td>$R = 100 \text{ m}, \sigma = 12 \text{ dB}$</td>
<td>$2.1275 \times 10^{-4} \text{ dB}$</td>
<td>$0.0012 \text{ dB}$</td>
</tr>
</tbody>
</table>

Table 4.2: Error analysis.

### 4.3 Star-node Detection

#### 4.3.1 Background

Self-configuring, hierarchical, *ad hoc*, wireless networks are fast becoming the focus of research for spectral efficiency and energy efficiency reasons. Such networks can be considered as graphs where a node represents a transceiving unit and an edge represents a communication link between two nodes. In order to probabilistically analyse connectedness issues in such graphs, the concept of the *star-node* is introduced, where a star-node is a node whose path loss to multiple nodes in its vicinity falls below a given threshold, *i.e.*, it is capable of sustaining viable communication links to multiple neighbours. Star-nodes are important in the context of
Figure 4.1: Path loss distribution pdfs for uniformly distributed nodes in circles and hexagons having the same radii. Simulations match theory perfectly as scenario radii and standard deviations of the log-normal component are varied. It is interesting to note that the distribution of path losses for the hexagonal case is very closely approximated by the distribution of path losses for uniformly distributed nodes in a circle (a). The corresponding CDFs (b).
ad hoc and sensor networks since nodes in a self-configuring network must be able to identify their neighbours, i.e., those nodes with which viable communication links can be established. In this section, the probability of finding such star-nodes is analytically derived for a uniform user distribution in a circular scenario. The theory is tested against Monte Carlo simulations and a very good match has been found.

Star-nodes are especially significant in the context of hotspots that are typically found in urban cellular networks. The concept of the star-node is formally introduced later in this section. It is seen that the GUE can be considered to be a special type of star-node. A priori knowledge of the probability of the existence of a star-node in a network containing $n$ nodes is important for the establishment of a hierarchical network, like the one dealt with in Chapter 3.

One of the most powerful methods of boosting wireless capacity is by shrinking the cell size. The reason for this is that smaller cell sizes enable the efficient spatial reuse of spectrum [3]. An added advantage is that the shorter transmission distances require lesser transmit power (green radio). However, reusing resources leads to an increase in interference. Therefore, future wireless network solutions are envisaged to be characterised by the lack of frequency planning [104], whereby free resources are opportunistically used. Dynamic, ad hoc, self-organising and spectrum-sharing networks using pico/femto-cellular structures are considered as improvements to the current wireless network deployments which do not efficiently utilise the available bandwidth. Making use of existing infrastructure and assigning a GUE to each hotspot of users [81] is one such proposal. This GUE then communicates with the BS, thereby doing away with the need for each individual UE to communicate with the BS.

In order to mathematically analyse such scenarios, the concept of the star-node is introduced. Consider a graph consisting of $n$ nodes/vertices. The degree of a node is defined as the number of edges incident to it. We define three types of nodes: a star-node is a node that has degree at least $k$ ($3 \leq k \leq n-1$), a chain-node, on the other hand, is one whose degree is exactly 2 and an end-node is a node with degree exactly 1. Two nodes are joined by an edge if the path loss between them falls below a pre-defined threshold, i.e., a viable communication link can be established between the two nodes. Beyond this point, only star-nodes are considered. The probability of the existence of a specified number of star-nodes in a graph of $n$ nodes is derived in this work. Fig. 4.2 shows the various types of nodes defined here. The conditions under which an edge exists between two nodes is described in Section 4.3.2.
Figure 4.2: The different types of nodes are showcased here. The degree of each node is recorded next to it. Nodes with degree $k = 1$ are known as end-nodes, those of degree $k = 2$ are known as chain-nodes and those of degree $k \geq 3$ are generally known as star-nodes. Star-nodes are of interest in this work.

In [105], the authors show the relation between $k$-connectivity (a graph is $k$-connected if there is no set of $k - 1$ nodes whose removal will partition the graph) in a network of $n$ nodes and their transmission ranges. A transmission range, $\delta$, is defined such that two nodes within a distance $\delta$ of one another are said to be capable of sustaining communication with one another. The value for $\delta$ is calculated such that the network still remains $k$-connected with a certain probability, i.e., the network is capable of sustaining $k - 1$ link faults. In that work, the lower bound for the probability of a network consisting of $n$ nodes ($n > k > 0$) being $(k + 1)$-connected has been calculated. However, these results are valid only for very dense networks, i.e., $n \gg 500$.

In contrast to the work presented in [105], in the following, we consider two nodes to be within communication range of one another if the path loss between them falls below some pre-defined threshold. This is a more natural assumption than the distance-based approach used in [105] because the path loss also includes a random log-normal shadowing component which can cause two nodes that are close to one another to be out of communication range. Since the work presented here is done in the context of hotspots, where the number of nodes/users is $n \ll 500$, the theory presented in [105] is not applicable.

The theory described in this chapter lends itself very elegantly to the analysis of ad hoc and
sensor networks. It can be used to find the number of well-connected nodes in a randomly deployed sensor network over a given area. Conversely, it can also be used to find the ideal node density if the required number of well-connected nodes and network coverage area is known \textit{a priori}.

### 4.3.2 Random Graphs

In the following sections, random graph theory, first introduced in [106], will be used to derive results pertaining to star-node detection. The theory of random graphs lies at the intersection between graph theory and probability theory, and studies the properties of typical random graphs. A random graph is obtained by starting with a set of \( n \) vertices and adding edges between them at random. Different random graph models produce different probability distributions on graphs. We deal specifically with the Erdos-Renyi model, commonly denoted as \( G(n, p) \) in which each of the \( \binom{n}{2} \) possible edges occurs independently and with probability \( p \). Random geometric graph theory [107] takes into account the physical proximity of the nodes, \textit{i.e.}, the probability of an edge existing between two nodes, \( p \), is dependent on the distance between them. However, due to the asymptotic nature of its results, it is outside of the scope of this work.

### 4.3.3 Star-Node Detection

From Section 4.2, we have seen that the pdf of path loss distribution between uniformly distributed nodes in a circular hotspot of radius \( R_h \) has been found to be

\[
    f_L(\ell) = \frac{(\ln 10)}{bR_h^2} \exp \{C\} \left[1 - \text{erf} (D)\right]; \quad \forall \ell, \tag{4.5}
\]

where \( L \) is the path loss between two points, \( \ell \) is the random variable associated with \( L \),

\[
    C = \frac{2(\ln 10)(\ell-a)}{b} + \frac{2\sigma^2(\ln 10)^2}{b^2},
\]

and

\[
    D = \frac{\ell b-a-b^2 \log_{10} R_h+2\sigma^2(\ln 10)}{\sqrt{2b}\sigma}.
\]

For the rest of this section, \( p \) (edge probability) is used to denote the probability with which two nodes are connected to one another via a sustainable communication link, \textit{i.e.}, an edge, using the Erdos-Renyi random graph model. The CDF associated with the pdf described by (4.5) shows the relationship between \( p \) and the path loss value. This can also be seen in Fig. 4.3 where the pdf of path loss distribution between nodes in a circle for a particular set of \( R_h \) and \( \sigma \) values is plotted in Fig. 4.3. The corresponding CDF shown in Fig. 4.3(b) clearly shows the
link between a certain path loss value and the corresponding value of \( p \). Thus, the value of \( p \) is

![Path Loss Distribution](image)

(a) pdf

![CDF](image)

(b) CDF

**Figure 4.3:** Path loss distribution pdf for uniformly distributed nodes in a circle of radius \( R_h = 100 \) m and log-normal shadowing standard deviation \( \sigma = 6 \) dB (a). The corresponding CDF showing the relationship between path loss threshold and \( p \), the probability of the existence of an edge (b).

directly related to the path loss threshold, \( i.e. \), the probability that two nodes are connected to one another via a healthy link increases if the path loss threshold is increased and vice-versa.

We now define two different varieties of star-nodes. A node that is of degree exactly \( k \), \( i.e. \) a star-node having healthy links to exactly \( k \) other nodes is denoted as a “\( k \)-star-node”. Similarly, “\( K \)-star-node” is used to denote a node of degree at least \( k \), \( i.e. \) a star-node having healthy links to at least \( k \) other nodes. Finally, “\( X_k \)” is used to denote the number of \( k \)-star-nodes in a given graph and “\( Y_k \)” denotes the number of \( K \)-star-nodes in a given graph. In the context of hotspots, it is more useful to know the probability of detecting one or more \( K \)-star-nodes since the GUE must be well placed to have good communication links with all other UEs belonging to the hotspot.

### 4.3.3.1 Probability of detecting at least one \( K \)-star-node

It has been shown in [106] that the probability of detecting exactly \( r \) \( k \)-star-nodes, \( P(X_k = r) \), is

\[
P(X_k = r) \sim e^{-\lambda_k} \frac{\lambda_k^r}{r!},
\]

(4.6)

where \( \lambda_k = nb(k; n-1, p) = n \binom{n-1}{k} p^k q^{n-k-1} \) and \( q = 1 - p \) and \( n \) is the number of nodes in the graph. In (4.6), the asymptotic relation is introduced. Two functions \( h(n) \) and \( g(n) \) are
said to be asymptotically equal to one another if \( \lim_{n \to \infty} \frac{b(n)}{g(n)} = 1 \). This asymptotic relation (\( \sim \) notation) is used extensively in the following section. If a graph with 40 nodes is considered, the total number of labelled graphs possible with 40 nodes is \( 2^{\binom{40}{2}} \approx 6.3591 \times 10^{234} \), which, for practical intents and purposes approaches infinity.

Let \( \mu_k = n B(k; n - 1, p) = n \sum_{j \geq k} b(j; n - 1, p) = n \sum_{j \geq k} \binom{n-1}{j} p^j q^{n-j-1} \), where \( b(j; n - 1, p) \) is the definition of the binomial distribution with parameters \( n - 1 \) and \( p \). The assertion of (4.6) holds if \( X_k \) is replaced by \( Y_k \) and \( \lambda_k \) by \( \mu_k \). Thus, the probability of finding exactly \( r \) \( K \)-star-nodes, i.e. \( P(Y_k = r) \) changes to

\[
P(Y_k = r) \sim e^{-\mu_k} \frac{\mu_k^r}{r!}.
\] (4.7)

The probability of detecting at least one \( K \)-star-node is of interest here. The probability of detecting no \( K \)-star-nodes is used to arrive at the required probability. Therefore,

\[
P(Y_k = 0) \sim e^{-\mu_k} \sim e^{-n \sum_{j \geq k} \binom{n-1}{j} p^j q^{n-j-1}}.
\] (4.8)

The probability of detecting at least one \( K \)-star-node can be calculated using (4.8) as

\[
P(Y_k \geq 1) = 1 - P(Y_k = 0) \sim 1 - e^{-n \sum_{j \geq k} \binom{n-1}{j} p^j q^{n-j-1}}.
\] (4.9)

The asymptotic probability that a graph consisting of \( n \) nodes distributed uniformly within a circle of a certain radius contains at least one star-node for a given edge probability, \( p \), i.e., it holds as \( n \to \infty \), is given by (4.9). A non-asymptotic probability for the detection of at least one star-node is now derived.

Consider a fully connected graph consisting of \( n \) nodes which are uniformly distributed in a circular area. Let \( M = \binom{n}{2} = \frac{n(n-1)}{2} \) denote the maximum number of possible edges in this graph. For a particular edge probability \( p \), the expected value of the number of edges in the
A Mathematical Treatment of Hotspots

graph is $Mp$. Using this, the expected value of the number of edges per node is

$$E(n_e) = \frac{2}{n}Mp = (n - 1)p. \quad (4.10)$$

The factor of 2 is introduced in (4.10) because every pair of nodes is joined by an edge.

For a node to qualify as a $K$-star-node, it must have at least $k$ edges originating from it. Putting this in (4.10) and rearranging gives $p = \frac{k}{n-1}$. If this condition is met, then every node has, on average, $k$ edges originating from it. Thus the average number of edges in the graph is $Mp = \frac{kn}{2}$. Therefore, if it is ensured that the graph contains at least $\frac{kn}{2}$ edges, then it contains at least one $K$-star-node. The rationale behind this statement is as follows: if the mean of an ensemble of values is $m$, then there must be at least one value $\geq m$. Using this argument, the guarantee or confidence of detecting at least one star-node for a graph consisting of $n$ nodes with an edge probability of $p$ is given by the binomial distribution function as

$$P_{\text{guar}}(Y_k \geq 1) = \sum_{j=\left\lceil \frac{kn}{2} \right\rceil}^{M} \left( \begin{array}{c} M \\ j \end{array} \right) p^j q^{M-j}$$

$$= 1 - \sum_{j=0}^{\left\lceil \frac{kn}{2} \right\rceil - 1} \left( \begin{array}{c} M \\ j \end{array} \right) p^j q^{M-j} \quad (4.11)$$

where $\lceil . \rceil$ denotes the ceiling function. Fig. 4.4 makes this clearer through an example. The binomial probability is calculated and plotted in for a graph with $n = 5$ and $p = 0.5$. The graph consisting of $5 < \left\lceil \frac{5k}{2} \right\rceil$ edges is shown on the left. It is seen here, that for these many edges, under certain edge configurations, the graph may contain one or more star-nodes but there will also be cases when there are no star-nodes (as shown in this case). The same graph consisting of $\left\lceil \frac{5k}{2} \right\rceil = 8$ edges is shown on the right. Here, it is seen that regardless of the configuration of the edges, the graph will always contain at least one $K$-star-node. Eq. (4.11) calculates the probability of the graph having $\left\lceil \frac{kn}{2} \right\rceil$ or more edges for a certain value of $p$. Such graphs will contain at least one $K$-star-node.

The probability described by (4.11) clearly overshoots the probability described in (4.9) because those graphs containing $K$-star-nodes in which the number of edges is $< \left\lceil \frac{kn}{2} \right\rceil$ are disregarded. This causes the probability of detection of at least one $K$-star-node using (4.11) to be lower than that calculated using (4.9) for any value of $p$. However, unlike (4.9), this simple probability is
A Mathematical Treatment of Hotspots

Figure 4.4: A graphical explanation for the probability described by (4.11). The graph on the left does not contain a K-star-node due to the configuration of the edges, whereas the graph on the right is guaranteed to contain at least one K-star-node, regardless of the edge configuration because it contains 8 edges.

not asymptotic in nature and holds for even very small values of $n$.

For $p \ll 1$ and $n \gg 1$, the binomial probability in (4.11) can be approximated with the Poisson law as $b(k; n, p) \approx \frac{a^k}{k!}e^{-a}$ [46], where $a = np$. Thus, (4.11) becomes

$$P_{\text{guar}}(Y_k \geq 1) = 1 - \sum_{j=0}^{\left\lceil \frac{kn}{2} \right\rceil} \frac{\vartheta^j}{j!}e^{-\vartheta},$$

(4.12)

where $\vartheta = Mp$. The CDF of the Poisson distribution can be expressed as $\sum_{k=0}^{l-1} \frac{a^k}{k!}e^{-a} = \frac{\Gamma(l, a)}{(l-1)!}$, where $\Gamma(l, a) = \int_{a}^{\infty} t^{l-1}e^{-t}dt$ is the upper incomplete Gamma function. Thus (4.12) becomes

$$P_{\text{guar}}(Y_k \geq 1) = 1 - \frac{\Gamma\left(\left\lfloor \frac{kn}{2} \right\rfloor, \vartheta\right)}{\left(\left\lfloor \frac{kn}{2} \right\rfloor - 1\right)!}$$

(4.13)

This is an equivalent representation of (4.11). It can be used for large values of $n$ since it does not deal with $M$, which increases quadratically with $n$. 

\[ \begin{align*}
p &= .5 \\
n &= 5 \\
k &= 3 \\
M &= 10 \\
\left\lfloor \frac{kn}{2} \right\rfloor &= 8 \end{align*} \]
4.3.3.2 Probability of detecting exactly one \( k \)-star-node and exactly one \( K \)-star-node

First, we find the probability that a graph contains exactly one \( k \)-star-node. Therefore, a graph containing any nodes of degree higher or lower than \( k \) does not fall into this category. Using (4.6), this probability can easily be found as the probability of detecting one \( k \)-star-node and zero star-nodes of degree \( > k \), \( i.e., \):

\[
P(X_k = 1 \land X_{>k} = 0) = e^{-\lambda_k} \lambda_k \prod_{i=k+1}^{n-1} e^{-\lambda_i}.
\]

(4.14)

Practically, from the point of view of sensor networks and hotspots, the most useful probability is that of detecting exactly one \( K \)-star-node from \( n \) uniformly distributed nodes in a circular scenario, \( i.e., \), \( P(Y_k = 1) \) since the existence of a star-node is a prerequisite for being able to establish a hierarchical network where the star-node acts as cluster head, \( i.e., \), the GUE. Arriving at this probability is straightforward as presented in [106] as

\[
P(Y_k = 1) = e^{-\mu_k} \mu_k.
\]

(4.15)

4.3.4 Results

A network of uniformly distributed nodes in a circular area is assumed. As in Section 4.2.3, the simulation parameters are taken from [94]. Table 4.3 contains the simulation parameters used.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Path loss parameter, ( a )</td>
<td>37 dB</td>
</tr>
<tr>
<td>Path loss parameter, ( b )</td>
<td>30</td>
</tr>
<tr>
<td>Radius, ( R_h )</td>
<td>100 m</td>
</tr>
<tr>
<td>Log-normal shadowing standard deviation, ( \sigma )</td>
<td>6 dB</td>
</tr>
<tr>
<td>Number of nodes</td>
<td>40 &amp; 60</td>
</tr>
</tbody>
</table>

Table 4.3: Simulation parameters.

The CDF associated with (4.5) is used to map the relationship between edge probability, \( p \) and the path loss threshold. This is then used to calculate the theoretical probabilities described in (4.6) through (4.15). These are compared against simulations in order to test their accuracy. The results show that in spite of the asymptotic nature of random graph theory, there is a strong match between simulations and theory. In each case, the probability of star-node detection is
shown for varying values of path loss thresholds as well as the corresponding edge probabilities, \( p \).

The probability of detecting at least one \( K \)-star-node as described by (4.9) is shown in Fig 4.5. Here, the probabilities of detecting at least one \( K \)-star-node from 40 and 60 uniformly distributed nodes are shown. It is seen that the probability of star-node detection increases as the path loss threshold is increased. This is obvious, since an increase in the path loss threshold translates directly to an increase in the edge probability (shown on the upper x-axis). It is also seen that as the density of nodes is decreased, the curve shifts to the right. As the density of nodes is reduced, the average distance between nodes increases. Therefore, for the same path loss threshold, the probability of star-node detection is reduced for lower node densities. For the scenario shown in the figure, node density is \( \sim 1273 \) nodes per sq. km. for the 40 node case and \( \sim 1910 \) nodes per sq. km. in the 60 node case. Finally, it is interesting to note the range of \( p \) values on the upper x-axis of this figure. For the 60 node case, to achieve 90% probability of star-node detection, the required edge probability is \( \sim .033 \) and it reduces to \( \sim .02 \) for 10% probability of detection. This shows that the probability of the existence of a star-node is very sensitive to the edge probability, \( p \).

Fig. 4.6 shows the probability of detection of at least one \( K \)-star-node using the tighter approach described by (4.13) from a network consisting of 40 and 60 uniformly distributed nodes. The
The detection of least one $K$-star-node (where $K = 3$) in a circular scenario of radius 100 m for 40 and 60 nodes. In this case, the theory described using (4.13) is used.

Figure 4.6: The detection of least one $K$-star-node (where $K = 3$) in a circular scenario of radius 100 m for 40 and 60 nodes. In this case, the theory described using (4.13) is used.

Curves in Figs. 4.5 and 4.6 are very similar in shape, however, it is clear that the curves depicted in Fig. 4.6 are offset to the right. For the same probability of star-node detection, using the approach described by (4.13) requires the path loss threshold to be set higher than the approach described by (4.9). This is because in this case, the probability of star-node detection requires that the average number of edges in the network is at least $\left\lceil \frac{kn}{2} \right\rceil$, which, as explained, disregards a whole class of graphs in which a star-node may exist (namely those cases when the total number of edges in the graph is $< \left\lceil \frac{kn}{2} \right\rceil$, but the edge configuration is such that one or more star-nodes exist). Thus, in order to enforce the new star-node detection condition, the path loss threshold must be higher than in the previous case. The set of curves shown in this figure are even more sensitive to changes in the path loss threshold. For example, in the 60 node case, to increase the guarantee of detection from 10% to 90% requires an increase in the threshold of only 2 dB (from 74 dB to 76 dB). This shows that the system is very sensitive to even a small change in threshold values. This confirms the so-called 0-1 law (discovered by Erdos and Renyi [106]) which states that many important properties (such as graph connectedness, in this case) of random graphs develop quite suddenly.

Fig. 4.7 shows the probabilities for the detection of exactly one $k$-star-node and $K$-star-node as described by (4.14) and (4.15), respectively. The shape of the curves is explained by the fact that at extremely low path loss thresholds, it is very unlikely that a node has several edges originating from it. However, as the threshold is increased, a critical level is reached, at which
A Mathematical Treatment of Hotspots

Figure 4.7: The probability of detecting exactly one \( k \)-star-node and \( K \)-star-node (where \( k = 3 \)) from 40 uniformly distributed nodes in a circular scenario of radius 100 m.

point, the likelihood of the graph containing exactly one node of the desired degree is the highest. Beyond this point, as the path loss criterion gets more relaxed, nodes of degrees higher than \( k \) begin to emerge, which then reduces the probability of the graph containing exactly one \( k \)-star-node or \( K \)-star-node with all other nodes of degree \(< k \). Furthermore, the probability of detecting exactly one \( K \)-star-node is higher than the probability of detecting exactly one \( k \)-star-node for any path loss value because \( K \)-star-node detection is \( k \)-star-node detection in addition to the detection of star-nodes with degrees higher than \( k \). Therefore, \( k \)-star-node detection can be considered as a subset of \( K \)-star-node detection.

Finally, the probability of detecting exactly 10 \( K \)-star-nodes from among 100 randomly distributed nodes is shown in Fig. 4.8. The results of the simulation are shown in Fig. 4.8(a). In order to visualise this situation, Fig. 4.8(b) shows one instance of a 100 node network with exactly four detected \( K \)-star-nodes. The path loss threshold is set to 65 dB in this case. In order to avoid cluttering, only the first three healthy links are shown for every detected star-node. The links are labelled with their path loss values (in dB). It can be seen that some nodes that are separated by large distances have smaller path losses than shorter links which is a direct consequence of log-normal shadowing.
Figure 4.8: The probability of detecting exactly 10 K-star-nodes \((k = 3)\) from 100 uniformly distributed nodes in a circular scenario of radius 100 m (a). Four clusters detected from 100 users uniformly distributed in a circle of radius 100 m. The healthy links are indicated and labelled with their path loss values in dB (b).

4.4 Summary

In Section 4.2, an analytical derivation of the pdf of path loss distribution between the centre of a circle and uniformly distributed nodes within it has been presented. An exact match between theory and simulations has been found. In addition, it has been shown that the theory presented is a very close approximation for the case when the nodes are uniformly distributed in a hexagon as is often done in cellular network simulations. The derived pdf assists in calculating the carrier-to-interference ratios, interference thresholds and exclusion regions in ad hoc and sensor networks. In addition, it is envisaged that the result can be used to develop and assess routing and scheduling algorithms for such networks without running time-consuming Monte Carlo simulations. Usually, a simulation is run by randomly dropping a set of nodes within a simulation area. The path losses between these nodes are individually computed, after which a scheduling/routing/etc., algorithm is applied. Clearly, the most time-consuming part of this operation is the calculation of path losses since this needs to be done for every pair of transmitting and receiving nodes. Using the results shown in this chapter, since the distribution of path losses is known a priori, nodes need not be dropped within a simulation scenario and the associated path losses computed. The path losses can simply be extracted from the known distribution, thus completely avoiding the need for lengthy simulations. The rest of the simulation can then proceed unchanged.

In Section 4.3, the theory governing the existence and detection of so-called star-nodes has been derived using the results derived in Section 4.2.2. The pertinence of star-node detection theory
is apparent in the context of ad hoc and self-configuring sensor networks because the existence of star-nodes is instrumental in the establishment of a network hierarchy in decentralised and self-organising networks. This randomly developed structure can be exploited for intelligent and energy efficient routing, intelligent network control as well as radio resource allocation. This work also helps answer an important question in terms of ad hoc and sensor networks: at what node density can a cluster of transceiving nodes sustain communication in an ad hoc fashion? Finally, the implications of the 0-1 law have revealed very good design information about the minimum node density and link budget requirements (transmit power and receiver sensitivity) for ad hoc networks.

The next chapter begins by formally introducing femto-cells and discussing various issues associated with their deployment within cellular networks. A performance analysis study of different deployment configurations is then presented and the results are compared against those of a traditional, state-of-the-art cellular network.
Chapter 5

Femto-cell Deployment

5.1 Overview

The performance of a hybrid time division duplex (TDD) system embedded within a cellular system employing frequency division duplex (FDD) is analysed in Chapter 3. From that research, it has been identified that very high capacities can be achieved between the user equipments (UEs) belonging to a hotspot. However, it is seen that the wireless radio frequency (RF) link connecting the relay gateway UE (GUE) within each hotspot to the core network (CN) is the cause of a capacity bottleneck whereby the high achievable capacities within the hotspot cannot be satisfied by the macro-cell base station (BS) due to poor signal-to-interference-plus-noise ratios (SINRs) on the BS-GUE link. The work presented in this chapter aims to address this issue through the deployment of femto-cells such that a wired backhaul exists between the GUE and the outdoor macro-cell BS. This effectively nullifies the bottleneck problem caused by the wireless backhaul to the core network.

This chapter introduces the concept of femto-cells, which are a major focus of current research in the context of 4th Generation (4G) and future cellular networks. The research presented in this chapter is conducted in the framework of Long-Term Evolution Advanced (LTE-A) since there has recently been a significant amount of industry momentum building up to LTE-based femto-cells [108]. First, the femto-cell concept is introduced in detail in Section 5.2. Next, the different methods of access, open-access, closed-access and hybrid-access are discussed in Section 5.3. A brief description of the underlying proposals for implementation of such access...
schemes is also presented. Subsequently, in Section 5.4, the groundwork is laid for an extensive study on femto-cell deployment within a traditional cellular network. This study concentrates on open and closed-access femto-cells and compares the performance of these against a traditional cellular network [109, 110]. It will be shown through the results in Section 5.5 that femto-cell deployment, regardless of the access scheme has significant gains to offer in terms of system capacity, especially in indoor scenarios. This study also shows that in the context of closed-access femto-cellular systems, UEs trapped geographically within femto-cells but being served by the macro-cell BS undergo severe downlink (DL) interference from the nearby home BSs. This issue is addressed in detail in Chapter 6. Summarising remarks are provided in Section 5.6.

Using Long-Term Evolution (LTE) terminology, the home BS is henceforth referred to as the home evolved NodeB (HeNB) and the macro-cell BS is referred to as the evolved NodeB (eNB). UEs served by the HeNB are known as femto UEs and those served by the eNB are known as macro UEs. The collection of a HeNB and the femto UEs that it serves is known as the femto-cell. However, the terms “femto-cell” and “HeNB” are used interchangeably when there is no ambiguity.

5.2 Introduction

There is a growing demand for increased user and system capacity in wireless networks. Naturally, such rapidly increasing demand is served by higher bandwidth allocation, but since bandwidth is scarce and expensive, a key to substantial capacity enhancement is to improve the spatial reuse of radio frequency resources. One of the most powerful methods of boosting wireless capacity is by shrinking the size of the cell. The reason for this is that smaller cell sizes effectively increase spatial reuse of spectrum [68]. Furthermore, the shorter transmission distances enhance link capacity due to higher channel gains [111]. While decreasing the cell size boosts system capacity, the cost involved is becoming increasingly prohibitive due to the required installation of a large amount of new network infrastructure.

Studies indicate that a significant proportion of data traffic originates indoors [3]. Poor signal reception caused by high penetration losses through walls severely compromises the operation of indoor broadband data services. This suggests that those operators capable of providing high throughput indoors are likely to be more successful in generating revenue. Therefore, the
Femto-cell Deployment

concept of femto-cells has recently attracted considerable interest. 3rd Generation (3G) femto-cells are now being commercialised, while the specifications of Beyond 3G (B3G) femto-cells are currently discussed in standardisation bodies, such as 3GPP LTE. Femto-cells consist of user-deployed HeNBs, which are low-cost, low-power, short-range, plug-and-play BSs. The aim of HeNB deployment is to extend and improve macro-cell coverage to indoor areas. As HeNBs are connected to the CN via cable, they therefore offload indoor users from the macro-cell, thus potentially enhancing the capacity both indoors as well as outdoors.

A number of proposals have been made in recent years to increase indoor capacity. In [64], it has been proposed that buildings be equipped with distributed antennas in order to improve coverage. However, the implementation of this system requires careful installation of transmitters. The proposal in [65] calls for the separation of UEs based on their mobility classes and serving them within micro and macro-cell accordingly. This proposal requires dual-mode UEs since a different access method is used based on the mobility class within which the UE falls. In [5–7,81], the authors propose the TDD underlay concept. Owing to the asymmetric nature of traffic [8], one of the FDD bands (the underloaded one) can be split in time such that the HeNB transmits and receives information from its associated UEs in a TDD fashion, as discussed in Chapter 3.

In this and the next chapter, both the macro and femto-cell operate with the same radio frequency spectrum in the FDD mode, compliant with the specifications for B3G mobile communication systems [21]. The HeNB backhauls data through a wired broadband gateway (DSL/cable/Ethernet/etc.) to the cellular operator network as shown in Fig. 2.17.

There are several obvious advantages from femto-cell deployment, the most important of which is that the operator is able to concentrate on providing better service to the outdoor macro-cell UEs. Another benefit for operators is that broadband coverage is extended to the indoor environment, which, as has been mentioned in Section 2.4, has gained significant importance in recent times. Moreover, femto-cell deployment could potentially lead to an overall reduced energy consumption as penetration losses due to walls are circumvented [72], tying in with green radio initiatives.

HeNBs, however, are deployed without network planning. Since HeNBs operate on the same frequency bands as eNBs serving macro-cells, their deployment injects additional interference into the system [112]. Furthermore, questions regarding security are raised with the deployment
of HeNBs: “should the HeNB allow any UE in its vicinity to connect to it?” or “should the HeNB maintain a list of UEs that are exclusively allowed to use its resources?” and “who should control access to the HeNB?”. The discussion is therefore taken in the direction of the different methods of access available to UEs. There are three methods of access and these are discussed in Section 5.3.

Recently, femto-cell research has gained considerable interest. One of the first studies on this topic [113] investigates the geographic distribution of throughput for a deployment of open-access femto-cells in a cellular network. The impact of HeNB deployment on macro-cell performance is analysed in [114]. The focus of the work presented in this chapter is to conduct a rigorous assessment of the impact of femto-cell deployment on a traditional cellular network. We also analyse the differences between open and closed-access systems through extensive system-level simulations. Simulations are performed with indoor and outdoor users, who are distributed randomly. A system without HeNB deployment, where all users (indoors or outdoors) are exclusively served by macro-cell eNBs (as in a traditional cellular system) serves as the benchmark system to compare against the systems with femto-cell deployment. Systems with HeNB deployment are distinguished between open and closed-access as discussed in Section 5.3. It is demonstrated that HeNB deployment, no matter what the access method is, has a clear advantage over the benchmark system in terms of user and overall system capacity.

5.3 Access Control Strategies

Naturally, since femto-cells are deployed independently by the users themselves, the users must be granted some level of control regarding the set of UEs that may be allowed access to the HeNB. In this light, three methods of access are usually associated with femto-cell deployment: open-access, closed-access and hybrid-access. Open-access femto-cells allow any UE to connect to the HeNB, whereas closed-access femto-cells only allow a specified set of UEs, known to belong to the closed subscriber group (CSG), to connect to the HeNB [115]. In principle, one UE may be a part of the CSGs of multiple femto-cells. It is expected that the owner of the femto-cell or a group of femto-cells is capable of maintaining and updating the CSG. Closed-access systems are more likely to impose high interference to indoor UEs that lie in close proximity to a femto-cell, but are not connected to its HeNB. A hybrid-access femto-cell allows access to all UEs, but with preferential access to a certain set of UEs. In the remainder of this chapter, we focus on only closed and open-access systems and compare them against
a benchmark system in which no HeNBs are deployed. Fig. 5.1 illustrates open and closed-access systems as well as the benchmark system. This figure also demonstrates how femto-cell deployment introduces additional interference to the system in comparison to traditional cellular networks.

**Figure 5.1:** The different femto-cell access methods and the benchmark system. Interference scenarios are highlighted with dashed lines.

Femto-cell specification in 3rd Generation Partnership Project (3GPP) started in Release 8, which has recently drawn to a close. The next phase of development will be conducted under the auspices of 3GPP Release 9. The remainder of this section briefly covers access control strategies and implementations in LTE systems.

There are already a limited number of femto-cell products available [108]. However, since specifications prior to Release 8 did not provide support for femto-cells, legacy UEs do not function with femto-cells in an optimal fashion. A pre-Release 8 UE will always attempt to camp on a femto-cell, even if the femto-cell is operating in the closed-access mode and the UE does not belong to that CSG. Clearly, this results in a degradation of the battery life of the UE and, in addition, increases the signalling overhead in the network. Release 8 UEs, with the ability to distinguish between a macro and a femto-cell, will avoid unnecessary camping on unallowed HeNBs, thereby increasing UE battery life and reducing the signalling burden on the network. The 3GPP TSG Core and Network Terminals WG1 has specified the required CN signalling which allows an update of the list of CSGs to which a UE may belong. Thus, the CSG concept allows UEs to make autonomous decisions on whether or not to camp on a femto-cell, depending on the associated CSG. The requirements specification on femto-cells has already been completed by 3GPP TSG SA WG1 [108, 116].

One way of linking femto-cells to the UEs that are allowed access to them is to define a CSG
identity that is unique within the public land mobile network (PLMN). Each femto-cell broadcasts this CSG identity and each UE stores the identities of the CSGs it is a member of. When the UE wanders into the coverage of a femto-cell, it can compare the broadcast CSG identity with its local list of CSG identities to determine whether it has access to the particular femto-cell or not [115, 117]. Every femto-cell broadcasts a CSG identity. In order for a UE to identify the access mode of a femto-cell, 3GPP has defined a CSG indicator [117, 118], which is a Boolean flag indicating whether the femto-cell is operating in open or closed-access mode. The CSG identity of an open-access femto-cell would remain empty. A UE that is not a member of any CSG will still need to read the CSG identity of any femto-cell to identify the access mode of that femto-cell. In an area of dense femto-cell deployment, this would result in the UE reading CSG identities of several femto-cells, leading to a reduction in battery life. Each LTE eNB broadcasts a specific physical cell identity (PCI) which is used by UEs to identify cells. In order to avoid the situation that a UE that is not a member of any CSG continues to read even the transmitted CSG identities of closed-access femto-cells, it is proposed that all closed-access HeNBs are allocated PCIs within a certain set and this set is stored locally at the UE [108, 118].

5.4 System Model and Simulation Setup

5.4.1 Capacity Calculation

An LTE orthogonal frequency division multiple access (OFDMA)-FDD system is considered in which the system bandwidth, $W$, is divided into $N_{RB}$ resource blocks (RBs), each of bandwidth $W_{RB}$ such that $W = N_{RB}W_{RB}$, where the RB represents the basic OFDMA time-frequency unit. Each RB is composed of several resource elements (REs) and two RBs comprise one subframe. Ten subframes together make one LTE frame. The make-up of one frame is shown in Fig. 5.2. In this initial study, the simulation is run over one subframe so as to gain an initial understanding of the potential benefits or pitfalls of femto-cell deployment. However, in the subsequent study shown in Chapter 6, the simulation is run for the duration of one entire frame. Universal frequency reuse is considered, so that both macro and femto-cells utilise the entire system bandwidth, $W$, in the uplink (UL) and DL. The set of available RBs, $\mathcal{N}$, with cardinality $|\mathcal{N}| = N_{RB}$, is distributed uniformly by eNBs and HeNBs among their associated macro and femto UEs respectively, for the UL and DL. Within the femto-cells, for closed-access systems, the HeNB allocates all UL and DL RBs to the one femto UE that the HeNB is associated with. In the case of open-access systems, if additional UEs from the macro-cell are assimilated into
Each 1 ms subframe consists of two RBs with each RB containing several REs of 15 kHz bandwidth each. Ten subframes together make one frame.

Throughout this and the following chapter, $u$ is used to identify any macro or femto UE and $v_u$ denotes the H/eNB which serves UE $u$. Multiple receive antennas are assumed, and the $M_{\text{ant}}$ received signal streams are combined with maximum ratio combining (MRC). The gain from MRC is approximated by simulating $M_{\text{ant}}$ individual, uncorrelated receive streams and adding the achieved SINR [17], since it is assumed that the receive antennas at the UE and eNB are sufficiently separated spatially. The received UL or DL signal power associated with UE $u$ on RB $n$, $Y_u^n$, is given by

$$Y_u^n = P_u^n \sum_{m} G_{m,n}^{u,v_u} + I_u^n + \eta_{\text{RB}}, \quad (5.1)$$

where $G_{m,n}^{u,v_u}$ is the channel gain between UE $u$ and its serving HeNB or eNB $v_u$, observed at receive antenna $m$ and at RB $n$. Furthermore, $\eta_{\text{RB}}$ accounts for thermal noise per RB which is constant across all RBs and both directions of communication. In the DL, the transmit power
Femto-cell Deployment

is set to $P_n^u = P_{eNB}$ and $P_n^u = P_{HeNB}$ if UE $u$ is served by an eNB or HeNB, respectively. In the UL, $P_n^u = P_{FUE}$ or $P_n^u = P_{MUE}$, depending on whether the UE in question is served by a HeNB or an eNB, respectively. The values $P_{HeNB}$, $P_{eNB}$, $P_{MUE}$ and $P_{FUE}$ are constant across all RBs. The aggregate interference $I_n^u$ is composed of macro and femto-cell interference

\[
I_n^u = \sum_{m} \left\{ \sum_{i \in M_{int}} G_{m,n}^{u,v} P_m + \sum_{i \in F_{int}} G_{m,n}^{u,v} P_f \right\},
\]

(5.2)

where the first and second addends represent the macro and femto-cell interference, respectively. Here, $P_m$ is set respectively to $P_{eNB}$ and $P_{MUE}$ in the DL and UL. Similarly, $P_f$ is set respectively to $P_{HeNB}$ and $P_{FUE}$ in the DL and UL. $M_{int}$ represents the set of interfering macro UEs in the UL and the set of interfering eNBs in the DL. Similarly, $F_{int}$ denotes the set of interfering femto UEs in the UL and the set of interfering HeNBs in the DL. In case UE $u$ is served by an eNB, $v_u$, in the DL, $M_{int}$ comprises all eNBs except for $v_u$, i.e., $v_u \notin M_{int}$ and $F_{int}$ is the set of all HeNBs in the system. In this case, for the UL, $u \notin M_{int}$ and again, $F_{int}$ is the set of all femto UEs in the system. Likewise, if UE $u$ is served by a HeNB $v_u$, then $v_u \notin F_{int}$ and $M_{int}$ contains all eNBs for the DL. In the UL, $u \notin F_{int}$ and $M_{int}$ comprises all macro UEs present in the system. The SINR observed in the UL or DL with regards to UE $u$ on RB $n$ amounts to

\[
\gamma_n^u = \frac{P_n^u \sum_{m} G_{m,n}^{u,v} P_m}{P_n^u + \eta_{RB}},
\]

(5.3)

where, once again, $P_n^u$ holds the appropriate transmit power value depending on the type of link and the direction of communication. Due to MRC at the receiver, the channel gains $G_{m,n}^{u,v}$ add constructively, so that the average SINR is increased by a factor of $M_{ant}$, together with an $M_{ant}$-fold diversity gain. Given the SINR and the number of served RBs, $|N_u|$, assigned to UE $u$, the capacity, $C_u$, is calculated by using the Shannon bound as

\[
C_u = \sum_{n \in N_u} W_{RB} \log_2 \left( 1 + \frac{\gamma_n^u}{\eta_{RB}} \right),
\]

(5.4)

5.4.2 Channel Model

The channel gain, $G_{m,n}^{u,v}$, between a transmitter $v$ and a receiver $u$, observed at receive antenna $m$ on RB $n$ as defined in (5.1), is composed of distance dependent path loss, log-normal
shadowing and channel variations due to frequency-selective fading:

\[ G_{m,n}^{u,v} = |H_{m,n}^{u,v}|^2 \left(10^{\frac{-L+X_\sigma}{10}}\right), \tag{5.5} \]

where \( H_{m,n}^{u,v} \) denotes the channel transfer function (CTF) between transmitter \( v \) and receiver \( u \), observed at receive antenna \( m \) and on RB \( n \), \( L \) is the distance-dependent path loss (in dB), and \( X_\sigma \) is the log-normal shadowing value (in dB) with standard deviation \( \sigma \), as described in [119]. Channel variations of \( H_{m,n}^{u,v} \) on different receive antennas are mutually independent. However, the path loss plus shadowing due to slow fading, \( L \), is identical for all receive antennas \( m \) and RBs \( n \) since this parameter depends on the spatial separation between transmitter and receiver. While the channel response generally exhibits time and frequency dispersions, channel fluctuations within a RB are neglected because the RB dimensions are significantly smaller than the coherence time and coherence bandwidth of the channel [120]. The delay profiles associated with applicable propagation scenarios of [119,121] are used to generate the frequency-selective fading CTF, \( H_{m,n}^{u,v} \).

5.4.3 Path Loss Models

Three path loss models (along with their respective delay profiles) as described in [119,121] are used – the urban micro (UMi) model for the macro-cell channel, the indoor hotspot (InH) model for the femto-cell channel and the indoor-to-outdoor model to simulate the channel between entities lying indoors and outdoors. For each link in the system, the probability of line-of-sight (LoS) is calculated as specified in the appropriate path loss model, and based on the LoS condition, the associated path loss model is applied to the respective link. Furthermore, a wall penetration loss is considered for the outdoor-to-indoor (and vice-versa) links.

5.4.3.1 UMi Model

This model is chosen because it is designed specifically for small cells with high user densities and traffic loads in city centres and dense urban areas. The path loss for the LoS condition is
calculated as

\[
L_{UMi,\text{LoS}} = \begin{cases} 
22 \log_{10}(d) + 42 + 20 \log_{10}(f_c[\text{GHz}]/5) ; & 10 \text{ m} < d < d'_{\text{BP}}, \\
40 \log_{10}(d) + 9.2 - 18 \log_{10}(h_{eNB}') \\
-18 \log_{10}(h_{UE}') + 2 \log_{10}(f_c[\text{GHz}]/5) ; & d'_{\text{BP}} < d < 5 \text{ km}.
\end{cases}
\] (5.6)

Here, the distance between transmitter and receiver is \(d\), the effective breakpoint distance is calculated as \(d'_{\text{BP}} = 4h_{eNB}'h_{UE}'f_c/c\), where \(f_c\) is the centre frequency in Hz, \(c\) is the speed of light in m/s and \(h_{eNB}'\) and \(h_{UE}'\) are the effective antenna heights for the eNB and UE, respectively, with values \(h_{eNB}' = 24\) m and \(h_{UE}' = 0.5\) m. Log-normal shadowing values are spatially correlated according to the correlation model in [119], where the values of their standard deviations can also be found. The path loss for the non-line-of-sight (nLoS) model is computed as

\[
L_{UMi,\text{nLoS}} = 36.7 \log_{10}(d) + 40.9 + 26 \log_{10}(f_c[\text{GHz}]/5) ; \quad 10 \text{ m} < d < 2 \text{ km}. \] (5.7)

The LoS probability is a function of distance and is calculated as

\[
\Pr(\text{LoS}) = \min \left(18/d, 1\right) \left(1 - e^{-d/36}\right) + e^{-d/36}. \] (5.8)

### 5.4.3.2 InH Model

This model is used to model the channel for links lying inside the femto-cells. The LoS path loss is calculated as

\[
L_{\text{InH,LoS}} = 16.9 \log_{10}(d) + 46.8 + 20 \log_{10}(f_c[\text{GHz}]/5) ; \quad 3 \text{ m} < d < 100 \text{ m}. \] (5.9)

The path loss for the nLoS model is calculated as

\[
L_{\text{InH,nLoS}} = 43.3 \log_{10}(d) + 25.5 + 20 \log_{10}(f_c[\text{GHz}]/5) ; \quad 10 \text{ m} < d < 150 \text{ m}. \] (5.10)
Finally, the probability of LoS for a link using the InH model is computed as

\[
\Pr (\text{LoS}) = \begin{cases} 
1; & d < 4, \\
e^{-\frac{d}{e}}; & 4 < d < 60, \\
0; & d > 60. 
\end{cases}
\] (5.11)

### 5.4.3.3 Outdoor-to-Indoor (and vice-versa) Model

The UMi path loss model assists in modelling the indoor↔outdoor path loss as

\[
L_{oi} = L_b + L_{tw} + L_{in}; \quad 50 \text{ m} < d < 5 \text{ km}. \] (5.12)

Here, \(L_b\) is the basic path loss calculated using the UMi model as \(L_b = L_{\text{UMi}}(d_{\text{out}} + d_{\text{in}})\). The parameters \(d_{\text{out}}\) and \(d_{\text{in}}\) refer to the outdoor and indoor distances respectively (see Fig. 5.3). The parameter \(L_{tw}\), is the wall penetration loss and \(L_{in}\), dependent on the indoor distance alone,

\[
L_{in} = 0.5d_{\text{in}}. \quad \text{In this case the probability of LoS is zero.}
\]

### Figure 5.3: Measurement of \(d_{\text{out}}\) and \(d_{\text{in}}\) for indoor↔outdoor path loss calculation.

5.4.4 Uplink Power Control

Power control is applied in the UL in both the femto and macro layer. According to [122], the transmit power per RB for UE \(u\), \(P_{\text{UE}}\), is adjusted as a function of the combined UL path loss and shadowing \(L\) as

\[
P_{\text{UE}} = \min \left\{ P_{\text{UE}}^{\max}, \max \left[ P_{\text{UE}}^{\min}, P_{\text{UE}}^{\max} \left( \frac{L}{\alpha} \right)^{\varsigma} \right] \right\}, \] (5.13)
where $P_{UE}$ is set to $P_{MUE}$ or $P_{FUE}$ depending on the serving entity if the UE in question. $P_{max}^\text{max}$ is the maximum transmit power per RB, $P_{min}^\text{min}$ is the minimum transmit power per RB and $\alpha$ is the $k$-percentile path loss, a constant whose value determines the critical path loss value above which a UE transmits with full power. The balancing factor, $\varsigma$, determines how steeply the transmit power increases with increasing path loss. Fig. 5.4 shows the variation of the transmit power per RB as a function of path loss according to the power control scheme (5.13) using the transmit power parameters as listed in Table 5.1. The value of $P_{min}$ is globally constant, independent of whether the femto or macro layer is being considered. However, the value of $P_{max}^\text{max}$ changes, depending on which layer is being considered. In the femto layer, the maximum femto UE transmit power, $P_{max}^\text{max}$, is set such that it cannot be higher than the HeNB transmit power, $P_{HeNB}$. Therefore, three different power control curves are shown in this figure for the femto layer.

![Figure 5.4: Demonstration of the UL power control scheme for increasing path loss values for the macro and femto layers.](image)

**5.4.5 User Distribution**

The simulation area comprises a two-tier, tessellated hexagonal cell distribution. In order to eliminate edge effects, an additional two tiers are simulated. However, statistics are taken only from the first two tiers. Femto-cells are circular, each with the same radius, and they are
uniformly distributed over the four-tier structure with a given density. One femto UE and one HeNB are randomly distributed within each femto-cell.

In the macro-cell, UEs are randomly distributed over the entire area. These UEs are served by the macro-cell and do not belong to any HeNB owner. Depending on their distribution density and the density of femto-cells, there is a certain probability that some of these UEs lie within a femto-cell. In the case of open-access systems such UEs are assimilated into the femto-cell. These are then served by the associated HeNB. Fig. 5.5 showcases a distribution of 15 femto-cells per macro-cell and 10 macro UEs per macro-cell.

![Diagram](image)

**Figure 5.5:** 15 femto-cells and 10 macro UEs per macro-cell. Femto UEs, HeNBs, macro UEs and eNBs are represented by blue dots, black crosses, red squares and green, labelled circles respectively. The inset focuses on a particularly densely populated region. Here, it is seen that some macro UEs lie within femto-cells.

For comparison, we also consider a benchmark system where the same set of UEs is maintained. In this case, all UEs are served by the macro-cell (whether located indoors or outdoors, whether previously belonging or not to a HeNB owner).

Once the users are distributed, log-normal shadowing maps containing correlated shadowing values in space are generated. Using these and the scenario specific path loss models described in Section 5.4.3, macro UEs are associated with the eNB to which they have the least path loss (including shadowing). Depending on whether open or closed-access is considered, macro UEs
that lie within femto-cells are either assimilated or left to communicate with the eNB lying outdoors.

5.5 Results

Simulations are run for a full-buffer traffic model, i.e., all users in the system are active simultaneously. Furthermore, the users are assumed to be stationary for the duration of the simulation. While, as mentioned in Section 5.4.2, the channel is assumed to be flat over the bandwidth of a RB, this is not the case when considering the entire bandwidth. Therefore, when considering the whole bandwidth, frequency selective fading is assumed such that different RBs at different frequency locations experience different fading. Perfect synchronisation in time and frequency is assumed so that interference between neighbouring RBs, i.e., adjacent carrier interference (ACI), is avoided. Based on the achieved SINR per RB, the aggregate capacity for UE $u$ is calculated as per (5.4). The parameters used in the simulation are taken from the 3GPP specifications [20, 21, 123–125] and are shown in Table 5.1. Although MRC has been introduced in Section 5.4.1, in the simulation results shown in this chapter, only one receive stream is assumed.

The overall sum system capacity for both UL and DL is depicted in Fig. 5.6. The benefit

![Figure 5.6: Sum system capacity for all three systems. The benefit of femto-cell deployment is clearly illustrated here.](image-url)
Table 5.1: Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average femto-cells per macro-cell</td>
<td>15</td>
</tr>
<tr>
<td>Average macro UEs per macro-cell</td>
<td>10</td>
</tr>
<tr>
<td>Femto UEs per femto-cell</td>
<td>1</td>
</tr>
<tr>
<td>Inter-site distance</td>
<td>200 m</td>
</tr>
<tr>
<td>Femto-cell radius</td>
<td>10 m</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>10 MHz</td>
</tr>
<tr>
<td>UL FDD band</td>
<td>2.505 GHz</td>
</tr>
<tr>
<td>DL FDD band</td>
<td>2.625 GHz</td>
</tr>
<tr>
<td>Total number of available RBs</td>
<td>50</td>
</tr>
<tr>
<td>RB Bandwidth</td>
<td>180 kHz</td>
</tr>
<tr>
<td>Thermal noise</td>
<td>$-174$ dBm/Hz</td>
</tr>
<tr>
<td>Total eNB transmit pow.</td>
<td>38 dBm</td>
</tr>
<tr>
<td>Total HeNB transmit pow.</td>
<td>$-30, -10 &amp; 20$ dBm</td>
</tr>
<tr>
<td>Maximum macro UE transmit pow.</td>
<td>24 dBm</td>
</tr>
<tr>
<td>Maximum femto UE transmit pow.</td>
<td>$-30, -10 &amp; 20$ dBm</td>
</tr>
<tr>
<td>Minimum macro/femto UE transmit pow.</td>
<td>$-30$ dBm</td>
</tr>
<tr>
<td>Wall penetration loss, $L_{tw}$</td>
<td>20 dB</td>
</tr>
<tr>
<td>$k$-percentile path loss, $\alpha$</td>
<td>124 dB</td>
</tr>
<tr>
<td>Path loss balancing factor, $\varsigma$</td>
<td>1</td>
</tr>
<tr>
<td>Number of receiving antennas, $M_{ant}$</td>
<td>1</td>
</tr>
</tbody>
</table>

of deploying femto-cells in a cellular system is clearly demonstrated in this figure. The sum system capacity is generated as the sum of the individual user capacities for users lying within the consideration area. For systems with HeNB deployment, the aggregate femto and macro user capacity is compared against the benchmark system where all users are served by the eNB only. These results highlight the achieved gains through HeNB deployment. It is seen that the sum capacity for systems with HeNB deployment is approximately two orders of magnitude higher than that for the benchmark system in both the UL and the DL. Certainly, without femto-cells, the benchmark system experiences the least interference in most cases (see, e.g., Figs. 5.8(a) and 5.10(a)). However, these gains are offset by the fact that in the benchmark the indoor (femto) users are not offloaded from the eNB. Since the same set of RBs are available to the eNBs in all systems, each user, on average, gets allocated fewer RBs in the benchmark system. These results illustrate how resources in a macro-cell can be effectively reused by femto-cells to significantly boost the overall system capacity. The remaining figures in this
section highlight similar trends with respect to the benchmark performance. For the closed and open-access systems, the DL sum system capacity increases as the HeNB transmit power is increased. This is because the higher transmit power in the DL results in an improved SINR at the UE. Due to the severe wall penetration losses, the increased transmit power results in a lower increase in interfering power than useful power. In the UL, due to power control, the output transmit power values are typically below the maximal power and as a result, the UL performance is independent of the maximum HeNB transmit power. In the benchmark system, since HeNBs do not exist, the capacity remains constant regardless the HeNB transmit power.

Before proceeding with the results in the remainder of this section, we define two sets of UEs:

**Set A:** Set A (femto) refers to all femto UEs in the system and Set A (macro) refers to all macro UEs in the system, regardless of whether they lie indoors or outdoors.

**Set B:** Set B refers to those macro UEs that lie within the coverage of femto-cells, i.e., those macro UEs lying physically within the confines of femto-cells.

The rest of this section is organised as follows: Sections 5.5.1 and 5.5.2 show the capacity and interference results pertaining to the DL and UL, respectively, for Set A. Section 5.5.3 shows user capacity and interference results for Set B.

### 5.5.1 Downlink

The cumulative distribution functions (CDFs) of the DL capacity for Set A (femto) for varying HeNB transmit powers is shown in Fig. 5.7. It is observed that an increase in HeNB transmit power improves DL user capacity for both open and closed-access. In this context, the more a curve is to the right, the better is the performance it is depicting. For example, we examine the open and closed-access performance of the 20 dBm case. We see that more than 10% of the open-access users have a capacity of less than 150 Mbps, whereas less than 10% of the closed-access users have a capacity of less than 150 Mbps, showing that the closed-access case outperforms the open-access case. This is expected, since the increased transmit power results in an increased SINR at the receiver. Furthermore, closed-access systems outperform open-access systems. This somewhat surprising result is attributed to the fact that in case of open-access, macro UEs that are located within the coverage of the HeNB will get assimilated into that femto-cell. In this case, the HeNB must distribute the available resources among
the femto UEs and the assimilated UE, thus resulting in each UE getting allocated fewer RBs compared to closed-access.

Fig. 5.8 shows the DL performance in terms of interference and capacity for set A (macro). Fig. 5.8(a) shows the interference experienced by macro UEs belonging to Set A for open and closed-access systems as well as for the benchmark system. The CDF for the interference in the benchmark system shows three distinct sections. The lowest interference regime spanning between $-180$ and $-120$ dBm corresponds to the interference experienced by indoor users. The middle portion corresponds to nLoS interference experienced by outdoor users and the last portion represents LoS interference experienced by outdoor users. The systems with femto-cell deployment are exposed to significantly more interference, since, unlike the benchmark system, most macro UEs are located outdoors, and outdoor UEs are not protected by building walls. Clearly, the higher the HeNB transmit power, the greater is the interference experienced by macro UEs. For closed-access, some indoor UEs are considered in the interference graph. These experience less macro interference, so that their interference CDF is superior to open-access at low HeNB transmit power. For high HeNB transmit power, femto interference dominates indoors and closed-access performance becomes worse than open-access.

The interference CDF is, however, not the only relevant metric. Since the intended signal
received from an eNB is strongly attenuated indoors and the amount of assigned resources per user differs across the various systems, the user capacity should also be considered in order to carry out a fair comparison. Fig. 5.8(b) depicts the CDF of user capacity for Set A (macro) in the DL for varying HeNB transmit powers. Here, the lower the HeNB transmit power, the better the DL performance of the macro UEs. This is expected, since the amount of interference originating from femto-cells is directly proportional to the HeNB transmit power. For this reason, it is seen that the best macro performance is achieved when the HeNB transmit power is at its lowest, \( i.e., -30 \) dBm. It is interesting to note that the systems with femto-cell deployment significantly outperform the benchmark system. This is due to the lower spatial reuse in the benchmark system, which means that the eNB has to share the available resources with a higher number of users. In this setting, with 15 femto-cells per macro-cell on average, each femto-cell serving one UE, eNBs in the benchmark system, need to serve more than twice the number of macro UEs, giving rise to poor benchmark user capacities.

### 5.5.2 Uplink

Fig. 5.9 shows the CDF of the UL capacity for Set A (femto). It is observed that the UEs achieve very high UL capacities within the femto-cells. Furthermore, closed-access slightly outperform open-access systems. This, again, is attributed to the fact that in case of open-access, macro UEs that are located within the coverage of the HeNB will get assimilated into that femto-cell. In this case, the HeNB must distribute the available resources among the femto UEs and the
Figure 5.9: UL capacity for Set A (femto) UEs in open and closed-access systems.

assimilated UE, thus resulting in each UE getting allocated fewer RBs compared to closed-access. This overcompensates the increased UL interference femto HeNBs experience from macro UE. In any case, the difference in overall capacity between open and closed-access is negligible since the probability that a macro UE lies indoors is low (approximately 6% with the user densities considered). It must be noted that due to the very short transmit distances within femto-cells, the power control scheme in the UL forces almost all UEs served by a HeNB to transmit with the lowest possible power (−30 dBm). This can be seen in Fig. 5.9, where the performance is very similar to the −30 dBm performance observed in Fig. 5.7.

Fig. 5.10 shows the performance of Set A (macro) in the UL. Fig. 5.10(a) shows the UL interference experienced by all macro UEs for open and closed-access systems as well as for the benchmark system. It is seen that that the trends of UL interference are substantially different from those of DL interference. All macro UEs are served by eNBs regardless of whether femto-cells are deployed or not. Since all eNBs lie outdoors and in the UL, interference is measured at the eNB, the corresponding CDFs do not exhibit such pronounced multi-modal distributions. There is no significant difference between open and closed-access, because UEs that get assimilated into open-access femto-cells are classified as femto UEs, and the UL interference their HeNBs experience is not reported in this figure. Similar to the DL results in Fig. 5.8(a), the benchmark system exhibits the least interference, due to the lack of active HeNBs.
Figure 5.10: UL interference per RB and capacity statistics for Set A (macro) UEs. Part (a) depicts overall UL interference and part (b) depicts overall UL capacity.

Fig. 5.10(b) shows the CDF of Set A (macro) capacity in the UL. The performance of the benchmark system is plotted for comparison. As expected, open-access outperforms closed-access, since macro UEs lying within femto-cells get assimilated and are served by the HeNB. This has a double impact on macro performance:

- These assimilated macro UEs get offloaded from the macro-cell, thus freeing up macro-cell resources.
- This user experiences a boost in capacity because the wall penetration losses are circumvented, transmission distances are reduced, and strong femto-cell interference is avoided. However, the actual performance difference is astonishingly small.

### 5.5.3 Set B: Affected Macro UEs

The user capacities of Set B UEs are shown in Fig. 5.11. Figs. 5.11(a) and 5.11(b) show the UL and DL capacities of such UEs in closed-access and open-access systems (notice the difference in scale of the x-axes), respectively. As expected, in the DL, for any HeNB transmit power, the DL capacity of Set B UEs is significantly higher for open-access than for closed-access systems. For closed-access, wall penetration losses and longer transmit distances drastically reduce capacity. Interestingly, for open-access, the UL performance is very similar to the DL performance when the HeNB transmit power is $-30$ dBm. This is because, as explained before, the power control algorithm forces almost all femto UEs to transmit with the lowest possible
power, which is $-30$ dBm.

For comparison with the overall case depicted in Fig. 5.8, the interference experienced in the DL by Set B UEs is presented in Fig. 5.12. This figure highlights the benefits of open-access as compared to closed-access in the context of DL interference. It is clearly seen from this figure that when an UE gets assimilated by a femto-cell, it undergoes a drastic reduction in interference. In fact, the level of interference experienced by assimilated UEs approaches that of the benchmark system, which can be considered to be the ideal case in terms of interference, since it does not contain any femto-to-macro interference. It is seen from this figure that in the case when the HeNB transmit power is at its highest, i.e., $20$ dBm, the difference in interference between open and closed-access systems is greater than $96$ dB. For open-access, since the interference is below the thermal noise floor, such a system is no longer interference-limited but noise-limited. Figs. 5.12 and 5.11(a) reveal a very important problem that is expected to be encountered in systems with closed-access femto-cell deployment: extremely severe DL interference originating from the HeNB, which renders the vulnerable macro UE incapable of achieving a useful DL SINR. A method of mitigating this interference is proposed and analysed in the subsequent chapter.

Finally, for completeness, Fig. 5.13 shows the UL interference experienced by Set B UEs. In the closed-access systems, these UEs are served by the eNB. Therefore, the closed-access CDF shows the UL interference observed by the outdoor-located eNBs. However, in the case of open-access systems, the macro UE gets handed over to the HeNB. As a result, due to
Figure 5.12: DL interference statistics for Set B UEs. Clearly, open-access systems impose severely reduced interference to the trapped indoor macro UEs.

Figure 5.13: UL interference statistics for Set B UEs.
wall penetration losses and the fact that in the UL, power control is used, the interference observed by HeNBs is significantly lower. The difference between the benchmark CDF and the closed-access CDF shows the level of additional intra-cell interference caused by femto-cell deployment.

5.6 Summary

Femto-cell deployment poses a viable complement to cellular networks. Operators need to bear low cost in their deployment since femto-cells are installed directly by the users themselves. Furthermore, since they share both the radio access scheme and the frequency band with eNBs, they are compatible with legacy UEs. Aside from these benefits, a cellular network stands to significantly gain in overall system throughput through the widespread deployment of HeNBs. Not only do HeNBs improve indoor coverage, bringing wireless broadband-like experience directly to indoor environments, but they also offload resources from the eNB, which can be utilised to improve coverage to outdoor users.

In terms of overall throughput, under the assumption of the femto-cell density used in this study, the difference between closed-access and open-access systems is almost negligible because of the relatively low probability that a macro UE lies inside a femto-cell. However, if a macro UE lies within a closed-access femto-cell, it might not be able to receive a DL transmission from its serving eNB because of high signal attenuation and, more importantly, very high interference from the nearby HeNB. If a closed-access femto-cell happens to contain a macro UE, there has to be a method of nullifying the DL interference experienced by this macro UE or else it will almost certainly go into outage. The subsequent chapter studies this issue, i.e., femto-to-macro DL interference in systems with closed-access femto-cells, more closely. A novel interference mitigation technique is proposed to control this particular interference scenario and extensive system-level simulations show the effectiveness of the proposed approach.
Chapter 6

Femto-cell Downlink Resource Partitioning

6.1 Overview

Summing up the research done so far in the context of femto-cells, we have seen from the work presented in Chapter 3 that there is a tremendous amount of capacity available for exploitation among clustered groups of indoor users in an urban scenario. However, in that work, due to the wireless nature of the link between the cluster gateway UE (GUE) and the core network (CN), the high indoor capacity demands cannot be satisfied. Research, therefore, has been taken in the direction of femto-cells, where the wireless link between the cluster of users and the CN is replaced by a wired one, as demonstrated in Chapter 5. This is how femto-cells are expected to be deployed in the coming years. This setup improves on the previous one by completely eliminating the bottleneck that exists between the CN and the cluster of users within the femto-cell. Chapter 5 discusses the various access strategies that are available to the user-deployed femto-cells. An especially critical scenario is that of a closed-access, co-channel femto-cell deployment within a traditional cellular network. The home evolved NodeB (HeNB) of such a femto-cell imposes strong downlink (DL) interference to nearby macro user equipments (UEs) that do not belong to the associated closed subscriber group (CSG) and are not permitted to hand over to that HeNB. It has been shown that macro UEs trapped within closed-access femto-cells are susceptible to very high DL interference originating from the HeNB serving the femto-cell. In future cellular networks containing embedded co-channel femto-cells, it is expected
that priority must lie with the macro user, i.e., satisfactory service must be guaranteed to the macro UE over the femto UE. In light of this, for closed-access femto-cells, it is of paramount importance that techniques are developed in order to reduce the detrimental DL femto-to-macro interference experienced by indoor macro UEs camped on the macro evolved NodeBs (eNBs).

The contribution in this chapter focuses on mitigating this DL femto-cell to macro-cell interference through dynamic resource partitioning, in the way that HeNBs are denied access to DL resources which are assigned to macro UEs in their vicinity [126–129]. By doing so, interference to the most vulnerable macro UEs is effectively controlled at the expense of a modest degradation in femto-cell capacity. The necessary signalling is conveyed through downlink high interference indicator (DL-HII) messages over the wired backbone. Extensive system level simulations demonstrate that by using resource partitioning, for a sacrifice of 4% of overall femto DL capacity, macro UEs exposed to high HeNB interference experience a ten-fold boost in capacity.

The rest of this chapter is constructed as follows: Section 6.2 briefly motivates the need for an analysis of interference in femto-cell-enabled cellular networks. A thorough introduction to the resource partitioning concept and possible methods of implementing it in Long-Term Evolution (LTE) networks is provided in Section 6.3. A few LTE-centric modifications to the system model and simulator setup introduced earlier in Chapter 5 are shown in Section 6.4. Section 6.5 contains results showcasing the benefits of resource partitioning applied to a cellular network with closed-access femto-cells embedded within it. Comparisons against a benchmark system without any deployed HeNBs are also presented in this section. Finally, Section 6.6 summarises the work presented in this chapter and contains concluding remarks.

### 6.2 Introduction

In this chapter, as in the previous one, both macro and femto-cells are assumed to operate in the same radio frequency spectrum in frequency division duplex (FDD) mode, compliant with the specifications for Beyond 3G (B3G) mobile communication systems [21]. Like in the original time division duplex (TDD) underlay concept [5], the HeNB backhauls data through a dedicated broadband gateway (DSL/cable/Ethernet/etc.) to the cellular operator network, as explained in Chapter 5.

However, HeNBs are deployed without network planning, such that their deployment intro-
duces additional interference [112]. Out of the access control schemes discussed in Section 5.3, the closed-access scheme is the most difficult to manage in terms of interference. This is because a foreign macro UE lying in the coverage area of a femto-cell is not allowed to communicate with that HeNB, but must communicate with the eNB which lies outdoors. Due to wall penetration losses, such macro UEs receive a highly attenuated signal from the eNB and, in addition, receive excessive interference originating from the HeNBs, whose coverage areas the macro UE lies in. Still, regardless of the method of access, it is crucial that the provision of base-coverage by the macro-cell network is not compromised by femto-cell deployment.

In [113], the feasibility of the co-existence of co-channel macro and femto-cells has been investigated. A power control method is defined in the DL such that a constant femto-cell radius is maintained. In [114], the authors analyse the impact of femto-cell deployment on the macro-cell performance. In all of these papers, no active interference avoidance technique is discussed. In [130], the authors analyse the uplink (UL) capacity and interference avoidance for networks consisting of macro and femto-cells existing together in a code division multiple access (CDMA) network. In particular, the authors evaluate a network-wide area spectral efficiency metric, which is defined as the feasible combinations of the average number of macro-cell UEs and HeNBs per eNB that satisfy a target outage constraint. Interference avoidance in this case is done via a time-hopped CDMA physical layer and sectorisation of antennas. In contrast to the above, the contribution in this chapter comes in the form of a novel dynamic DL interference avoidance technique which prioritises macro UEs for a spectrum sharing orthogonal frequency division multiple access (OFDMA) system. The reason for this is twofold. First, the DL is more critical in terms of femto-to-macro interference because it is more likely that a macro UE suffers from DL interference from a nearby HeNB than an eNB suffers from UL interference from a nearby femto UE, due to the asymmetry in cell-size, and the corresponding asymmetry in transmit powers between macro and femto-cells. Second, priority should generally be given to the macro layer rather than the femto layer. To this end, if a HeNB is perceived to interfere severely with a macro UE, it must act so as to nullify the interference it injects into the system by smartly scheduling (partitioning) its resources. If no macro UE is affected, the femto-cell uses all resources (full frequency reuse) as it would do in an open-access system.

For the B3G mobile communication system 3rd Generation Partnership Project (3GPP) LTE [21], high interference indicator (HII) messages are specified to deal with macro-to-macro interference in the UL [131, 132]. These are conveyed through the X2 interface via the wired
backbone. In this work, it is demonstrated that the same framework can be applied for DL interference coordination between macro and femto-cells, by signalling DL-HII messages via an X2 interface to femto-cells.

In order to assess the impact of resource partitioning on macro and femto-cell performance, system level simulations are carried out. The performance of a closed-access system is compared against the performance of the same distribution of users using the aforementioned resource partitioning scheme. For comparison purposes, a benchmark system is simulated which closely reflects state-of-the-art cellular networks in which there are no HeNBs, and all femto as well as macro UEs are served by eNBs.

6.3 Femto-Cell Resource Partitioning

6.3.1 Downlink Interference Scenario for Closed-Access

As the eNB transmit power typically exceeds the HeNB transmit power by several orders of magnitude, \( P_{\text{HeNB}} \ll P_{\text{eNB}} \), in most cases, the interference seen by macro UE \( u \) will be dominated by eNB interference. The values \( P_{\text{HeNB}} \) and \( P_{\text{eNB}} \) have already been introduced previously in (5.2). Only if a macro-cell receiver, UE \( u \), is located in close proximity to an interfering HeNB \( i \), UE \( u \) is exposed to high HeNB interference, \( G_{u,i}^n P_{\text{HeNB}, i} \in \mathcal{F}_{\text{int}} \). In case UE \( u \) is located indoors, the situation is exacerbated by the poor channel gains, \( G_{v,u}^n \), caused by high wall penetration losses, \( L_{\text{tw}} \). This UE \( u \) is likely to experience poor signal-to-interference-plus-noise ratio (SINR), (5.3). With full frequency reuse, femto-cells utilise all \( N_{\text{RB}} \) resource blocks (RBs). Therefore, the received SINR is likely to be unacceptable over the entire set of RBs allocated to UE \( u \), i.e., \( \mathcal{N}_u \).

6.3.2 Avoiding Femto-to-Macro Interference

Suppose that macro UE \( u \) is located indoors within coverage of an interfering HeNB \( i \), but served by an outdoor eNB \( v_u \). An effective means of mitigating the destructive HeNB interference observed by UE \( u \) is to introduce the concept of resource partitioning, such that HeNB \( i \) is denied access to the RBs, \( \mathcal{N}_u \), that are assigned to UE \( u \). In other words, the set of RBs allocated to UE \( u \) must be left idle by the HeNB \( i \). Doing so completely eliminates the interference originating from the interfering HeNB \( i \), which, in this case, is the most dominant source of
interference. This increases the SINR (5.3) achieved at the macro UE. This is demonstrated in Fig. 6.1

![Diagram](image_url)

**Figure 6.1:** Resource partitioning in the vicinity of a femto-cell. The femto-cell is forbidden from using the DL resources allocated to nearby macro UEs, i.e., b and c, but may continue using the set of resources a.

In order to implement femto-cell resource partitioning, a pre-defined interference threshold, $I_{\text{th}}$, is introduced. Each macro UE $u$ measures the average channel gains, $\bar{G}_{u,H_{u}} = \mathbb{E}\{G_{u,H_{u}}^m\}$, between itself and nearby HeNBs belonging to the set $H_{u}$ and performs the following threshold test

$$10 \log_{10} \mathbb{E}\{G_{u,H_{u}}^m\} = -L_{u,H_{u}}^m + X_{\sigma} \geq I_{\text{th}} - P_{\text{HeNB}} = G_{\text{th}} \quad (6.1)$$

In case the average channel gain between a HeNB and one or more vulnerable macro UEs exceeds $G_{\text{th}}$, the HeNB is instructed to perform resource partitioning by suppressing transmission on RBs that are reserved by the vulnerable macro UEs. Clearly, under the assumption that the environment remains unchanged, decreasing the value of $I_{\text{th}}$ while keeping $P_{\text{HeNB}}$ fixed, increases the size of the exclusion region and protects a larger number of macro UEs, as seen in Fig. 6.2. In this context, the exclusion region is that spatial area within which vulnerable macro UEs are protected through resource partitioning at the HeNB. Since the calculation of $I_{\text{th}}$ includes log-normal shadowing, the shape of the exclusion region is not deterministic, i.e., it is not circular. Therefore, the lower the threshold $I_{\text{th}}$, the more resources are partitioned by HeNBs, so that the impact of resource partitioning on femto-cell performance increases as $I_{\text{th}}$ decreases.
Femto-cell Downlink Resource Partitioning

It is possible that more than one macro UE experiences heavy interference from more than one HeNB. Suppose that HeNB \( i \) causes strong interference to several UEs, as determined by the threshold test (6.1). Let the set of macro UEs exposed to strong interference from HeNB \( i \) be denoted by \( \mathcal{U}_{i}^{\text{aff}} \). The associated measurement and signalling procedures on how each UE in \( \mathcal{U}_{i}^{\text{aff}} \) identifies the interfering HeNB \( i \) are detailed in Section 6.3.3. As per the resource partitioning concept, HeNB \( i \) must partition resources such that it does not cause interference to the set of macro UEs \( \mathcal{U}_{i}^{\text{aff}} \). In other words, the resources that are prohibited for HeNB \( i \), \( \overline{\mathcal{N}}_i \), are in the form

\[
\overline{\mathcal{N}}_i = \bigcup_{u \in \mathcal{U}_{i}^{\text{aff}}} \mathcal{N}_u . \tag{6.2}
\]

It must be noted that the affected macro UEs within \( \mathcal{U}_{i}^{\text{aff}} \) may be connected to different macro eNBs, as HeNB \( i \) may be within the coverage area of several macro-cells, \( e.g. \), if it lies at the conjunction of two or more macro-cells.

In general, every HeNB that causes high DL interference to nearby macro UEs must partition resources as explained by (6.2). However, due to the low HeNB transmit power, \( P_{\text{HeNB}} \), it is unlikely that many macro UEs experience heavy interference from the same femto-cell. Hence, only a small subset of the users served by an eNB are interfered by the same set of HeNBs as illustrated in Fig. 6.1. This implies that the number of RBs \( |\overline{\mathcal{N}}_i| = \overline{N}_i^{\text{RB}} \) that must not be used by an interfering HeNB is much smaller than the total number of RBs, \( \overline{N}_i^{\text{RB}} \ll N_{\text{RB}} \), so that the degradation of femto-cell capacity is expected to be modest.

Figure 6.2: Resource partitioning with two different thresholds \( (G_{\text{th}}^a > G_{\text{th}}^b) \). Using a lower threshold \( b \) leads to a larger number of partitioned resources.

(a) High interference threshold.  
(b) Low interference threshold.
6.3.3 Practical Implementation in LTE Systems

In order to implement the resource partitioning concept, the interfering femto-cell needs to be identified and then be informed of the restricted resources $\mathcal{N}_i$ it must not use according to (6.2). This involves integrating the proposed resource partitioning concept within the network architecture.

In abstract, femto-cell resource partitioning is integrated into the LTE network architecture by the following procedure:

1. Macro UE $u$ determines the physical cell identity (PCI) of surrounding HeNBs, by reading the corresponding broadcast channel (BCH), and stores them in a list containing neighbouring PCIs.

2. UE $u$ identifies the heavily interfering HeNBs in its proximity using reference signal received power (RSRP) measurements.

3. The PCIs of the corresponding HeNBs are reported to the serving eNB.

4. The eNB prepares a DL-HII bitmap containing information about which RBs are transmitted with high power.

5. The DL-HII bitmap is disseminated to neighbouring H/eNBs over the X2 or S1 interfaces.

6. If the receiving eNB is a HeNB, it will refrain from using the particular RBs marked in the DL-HII bitmap. In this way, the detrimental DL femto-cell interference at the vulnerable macro UEs is avoided.

The necessary UE measurements that identify which femto-cells are in close vicinity of a macro UE are similar to a handover procedure. In LTE, macro UEs read the BCH not only from their primary eNB, but also from one or several secondary eNBs. As the BCH contains the PCI details, a UE can establish a list of neighbouring eNBs. Knowledge of the PCI also enables the UEs to read the cell-specific reference signals (also known as training symbols or pilots) of neighbouring eNBs, which are needed to carry out RSRP measurements. These allow the UE to estimate the average channel gain between itself and the surrounding HeNBs, $\bar{G}_{u,H}^{u,H}$, in (6.1). RSRP, for a specific cell, is defined as the linear average over the power contributions (in W) of the resource elements (REs) which carry cell-specific reference signals within the considered measurement frequency bandwidth [21]. As HeNBs also broadcast their PCI in the BCH, as
well as cell specific reference signals, RSRP measurements allow the identification of HeNBs that are in close proximity of a macro UE. It is important to note that this does not introduce any additional overhead, since an existing signalling procedure between macro UEs and eNBs is utilised.

The eNB needs to inform the HeNB that causes interference of the restricted resources, $\overline{N}_i$, it must not use according to (6.2). This involves defining the transport of control information from eNBs to HeNBs using the LTE network architecture shown in Fig. 6.3. The S1 interface connects the serving gateway (S-GW)/mobility management entity (MME) with a pool of neighbouring eNBs. The MME is a control node which processes the signalling between the UE and the CN. Neighbouring eNBs are interconnected via the X2 interface, which conveys control information related to handover and interference coordination. The X2 interface is therefore particularly suited for signalling related to femto-to-macro interference avoidance [131, 132].

![Overall LTE architecture showing S1 and X2 interfaces. HeNBs are also expected to be connected via the X2 interface.](image)

**Figure 6.3:** Overall LTE architecture showing S1 and X2 interfaces. HeNBs are also expected to be connected via the X2 interface.

In LTE, the network architecture is flat such that when a UE is handed over, in order to improve latency and efficiency, the handover procedure is exclusively controlled by the source and destination eNBs [14]. For intra-LTE handover, the default procedure is that the source
eNB buffers the data and passes it to the destination eNB over the X2 interface. If no X2 interface exists between the source and destination eNBs, the handover is performed over the S1 interface. However, from the UE’s viewpoint, there is no difference between the two types of handover [14]. In the case of closed-access femto-cells, where a handover is not possible between a source H/eNB and a destination HeNB, the proposed resource partitioning procedure requires that signalling information is conveyed from the source eNB to the destination HeNB.

In the LTE DL, a bitmap known as the relative narrowband transmit power (RNTP) indicator is exchanged over the X2 interface between eNBs. The RNTP indicator is used by an eNB to signal to neighbouring eNBs on which RBs it intends to transmit with high power in the near future. Each bit of the RNTP indicator corresponds to one RB in the frequency domain and is used to inform the neighbouring eNBs if the eNB in question is planning to exceed the transmit power for that RB or not [133]. The value of the threshold and the time period for which the indicator is valid are configurable parameters. This bitmap is intended to enable neighbouring cells to estimate the amount of interference on each RB in future frames and therefore schedule their UEs accordingly. Furthermore, the source and destination cell IDs need is contained in the RNTP.

The DL-HII messages that indicate which resources a particular HeNB must not use may be conveyed by a bitmap that is equivalent to that of the RNTP indicator. Provided that HeNBs are also connected to the X2 interface, DL-HII messages emitted by eNBs may be configured to perform resource partitioning at certain HeNBs by using the format of the RNTP indicator. Suppose that macro UE \( u \) served by eNB \( v_u \) is trapped within the coverage area of a closed-access femto-cell, served by HeNB \( i \). Then resource partitioning is implemented by sending a DL-HII message to HeNB \( i \), where ones and zeros correspond to RBs where HeNB \( i \) may and may not transmit, respectively. The transmission format of the RNTP indicator is therefore perfectly suited for DL-HII messages.

In order to avoid that DL-HII messages are sent every subframe, i.e., at 1 ms intervals (in LTE), the lifetime of DL-HII messages could be configured in a dedicated field within the DL-HII message format. Depending on the underlying service the macro UE is using, the eNB estimates for how long the RBs utilised by macro UE are to be reserved, and notes this estimate as the lifetime of the DL-HII message. Unless the DL-HII message is updated before its lifetime expires, the HeNB may then reuse the restricted RBs after the lifetime of the DL-HII message has expired. This limits the signalling overhead due to DL-HII messages to a level comparable
to that of a handover procedure, which is needed, *e.g.*, for macro-to-femto-cell handover in open-access systems.

Historical UE information is propagated between eNBs during the X2 handover procedure [14]. Historical UE information consists of the last few cells visited by the UE, together with the time for which the UE was camped at that eNB. The historical information is used to determine the occurrence of a handover ping-pong between cells. This is also a source of information that is useful in the context of resource partitioning. If a UE is camped to the last few eNBs for a short time interval, the resource partitioning procedure need not be carried out. This can be done in order to avoid unnecessary signalling.

### 6.4 System-Level Simulation Setup

This section details the changes to the simulation setup in comparison to the setup described in Section 5.4 previously.

#### 6.4.1 System Model

In this chapter, only the DL of an OFDMA system is considered since priority is assumed to lie with the macro UE. The same resource allocation techniques as those detailed in Section 5.4 are used here. Received signal power, interference and SINR calculations remain the same as detailed through (5.1), (5.2) and (5.3), respectively. However, here, the system is improved by adopting a more realistic approach to capacity calculation. Previously, using the achieved SINRs on a user’s allocated RBs, the aggregate Shannon capacity has been calculated using (5.4). In this chapter, link adaptation is implemented, where the modulation and coding scheme used are selected based on the achieved SINR. In order to easily model link adaptation, the SINR is mapped to the capacity using the *attenuated and truncated Shannon bound* method [134]. Given a particular SINR, \( \gamma_n^u \), the spectral efficiency on RB \( n \) for UE \( u \), \( \rho_{n}^u \), is determined by

\[
\rho_{n}^u = \begin{cases} 
0 & \text{for } \gamma_{n}^u < \gamma_{\text{min}}, \\
\nu S(\gamma_{n}^u) & \text{for } \gamma_{\text{min}} < \gamma_{n}^u < \gamma_{\text{max}}, \\
\rho_{\text{max}} & \text{for } \gamma_{n}^u > \gamma_{\text{max}},
\end{cases}
\]  

(6.3)
where $S(x) = \log_2(1 + x)$ in [bps/Hz] is the normal Shannon bound, $\nu$ is the attenuation factor representing implementation losses and $\gamma_{\text{min}}$ and $\gamma_{\text{max}}$ are the minimum and maximum SINRs supported by the available modulation and coding schemes. These parameters are summarised in Table 6.1. The capacity, $C_u$, of UE $u$ is then calculated as the aggregate capacity on all the RBs allocated to it as

$$C_u = W_{\text{RB}} \sum_{i \in \mathcal{N}_u} \rho_i^u,$$

(6.4)

where $\mathcal{N}_u$ is the set of RBs allocated to user $u$. The value for $\gamma_{\text{max}}$ is taken from [135] based on a maximum modulation scheme of 64-QAM in the DL.

### 6.4.2 Path Loss Models

The path loss models used in this simulation are different from those listed in Section 5.4.3. Here, again, three path loss models are used depending on the type of link, based on 3GPP recommendations [136]. For a purely outdoor link, i.e., the link (useful or interfering) between an eNB and an outdoor macro UE, the path loss is calculated as

$$L [\text{dB}] = 15.3 + 37.6 \log_{10}(d),$$

(6.5)

where $d$ (in m) is the distance between the transmitter and the receiver.

When considering the useful/interfering link between an eNB and a macro UE situated indoors or the interfering link between a femto UE (which is always situated indoors) and an eNB, the path loss model (6.5) includes the wall penetration loss and is calculated as

$$L [\text{dB}] = 15.3 + 37.6 \log_{10}(d) + L_{\text{tw}},$$

(6.6)

where $L_{\text{tw}}$ is the wall penetration loss (in dB).
Finally, when considering the useful/interfering link between a HeNB and a femto UE or the interfering link between a macro UE and a HeNB, the path loss is calculated as

\[ L [\text{dB}] = 127 + 30 \log_{10} (d/1000) . \] (6.7)

This is a simplified model based on LTE-A evaluation methodology which avoids modelling any walls.

Log-normal shadowing is added to all links. Correlated shadowing maps are applied such that the correlation in the shadowing values of two points is dependent on the distance between them. Table 6.2 shows the shadowing standard deviation \( \sigma \) and auto-correlation shadowing distances for the macro and femto-cells, as prescribed in [136].

<table>
<thead>
<tr>
<th></th>
<th>Macro-cell</th>
<th>Femto-cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Deviation, ( \sigma )</td>
<td>8 dB</td>
<td>10 dB</td>
</tr>
<tr>
<td>Auto-correlation distance</td>
<td>50 m</td>
<td>3 m</td>
</tr>
</tbody>
</table>

Table 6.2: Shadowing Parameters.

6.4.3 User Distribution and Sectorised eNBs

The simulation area comprises a two-tier, tessellated hexagonal cell distribution. In order to eliminate edge effects with regards to interference, an additional two tiers are simulated. However statistics are taken only from the first two tiers. Deviating from the simulation setup used in Chapter 5, the sectorised eNBs are placed at the junction of three hexagonal cells, such that each eNB serves three sectors, with each sector reusing all frequency resources. For each sector, the azimuth antenna pattern, \( A(\theta) \), is described by [136]

\[ A(\theta) = - \min \left[ 12 \left( \frac{\theta}{\theta_{3dB}} \right)^2 , A_m \right] , \] (6.8)

where the \( \theta_{3dB}=70^\circ \) is the angle from the central lobe at which the gain reduces to half the maximum value and \( A_m=20 \text{ dB} \) is the maximum possible attenuation due to sectorisation.

In order to implement a more realistic femto-cell distribution, the simulation assumptions described in [136] are followed where a 5×5 grid model is used to simulate femto-cell deployment. This setup models a single-floor building with 25 apartments that are arranged in a 5×5...
A HeNB may exist in an apartment with probability $p_1$. Furthermore, a HeNB may be active with probability $p_2$. Therefore, the probability, $p_a$, that an apartment contains an active HeNB is given by $p_a = p_1 p_2$. Every active HeNB serves exactly one associated femto UE. These are dropped randomly and uniformly within the apartment with a specified minimum separation from the HeNB. In addition to this, macro UEs are also randomly and uniformly dropped within the tiered hexagonal system. As a result, it is possible that a macro UE lies within the confines of an apartment. Fig. 6.4 shows one instance of a distribution of four apartment blocks and ten macro UEs per macro sector. It is observed that some macro UEs lie within apartment blocks. A closed-access policy is assumed so that such macro UEs, despite their indoor location, are served by the outdoor eNB. In such a situation, these macro UEs suffer from severe interference originating from the nearby HeNBs. Macro UEs lying either inside an apartment containing active HeNBs or very close to such an apartment are the likely victims of high DL femto-to-macro interference. The concept of resource partitioning addresses the mitigation of interference experienced by such macro UEs in the DL, as already explained. The macro UEs indicated by arrows in Fig. 6.4 are the potential recipients of high interference originating from nearby femto-cells. In this particular case, if one or more HeNBs are indeed the cause

**Figure 6.4:** Four apartment blocks and ten macro UEs per macro sector. Macro UEs are denoted by red dots, femto UEs by blue diamonds, HeNBs by green crosses and eNBs by filled green circles, each labelled with a number. The close-up shows a few marked macro UEs undergoing potentially severe DL interference from nearby active femto-cells.
of high interference, they will partition resources so as to enable the vulnerable macro UEs to attain a satisfactory DL SINR.

6.4.4 Time Evolution

Since the resource allocation is random in nature, each run of the Monte Carlo simulation is iterated over a number of subframes (as opposed to just one subframe from Chapter 5) in order to obtain statistically accurate results. The simulation is run for the duration of ten subframes, i.e., one LTE frame. The time duration of the subframe, $t_s$, is listed in Table 6.3. At each subframe, the allocation of resources is randomised. It is assumed that the UEs are quasi-static for the duration of the run.

6.5 Results

The simulation is run for a full-buffer traffic model, which resembles the worst case scenario where all users in the system are active simultaneously. Moreover, time-domain changes in the channel due to fast fading between subframes are considered, such that for the same RB, the value of $H_{m,n}^{u,v}$ in (5.5) changes from subframe to subframe. Perfect synchronisation in time and frequency is assumed, such that interference between neighbouring RBs can be neglected as well. Relevant parameters used for the simulation are shown in Table 6.3.

Clearly, more than one macro UE can be affected by the same apartment block and more than one apartment block can affect the same macro UE (as demonstrated in Fig. 6.4). The offending HeNBs must then perform resource partitioning using the method described in Sections 6.3.2 and 6.3.3. Due to the effects of shadowing, the corresponding exclusion region is not a circular area.

For a meaningful performance assessment, the definition of affected macro and femto UEs is now introduced. A macro UE is said to be affected if its average channel gain to at least one HeNB exceeds the pre-defined threshold, $I_{1h}$, as defined in (6.1). This section shows results for different classes of UEs: overall macro (all macro UEs in the system, regardless of their location), overall femto (all femto UEs, all lying strictly indoors and served by an active HeNB), affected macro (only macro UEs in the vicinity of active femto-cells as described above) and affected femto (only femto UEs served by offending HeNBs).
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average 5×5 apartment blocks per macro-cell sector</td>
<td>{4, 14}</td>
</tr>
<tr>
<td>Average macro UEs per macro-cell sector</td>
<td>10</td>
</tr>
<tr>
<td>Inter-site distance</td>
<td>500 m</td>
</tr>
<tr>
<td>Individual apartment dimensions</td>
<td>10×10 m²</td>
</tr>
<tr>
<td>HeNB deployment probability, ( p_1 )</td>
<td>0.2</td>
</tr>
<tr>
<td>HeNB activation probability, ( p_2 )</td>
<td>0.5</td>
</tr>
<tr>
<td>Femto UEs per active femto-cell</td>
<td>1</td>
</tr>
<tr>
<td>DL FDD band</td>
<td>[2.62, 2.63] GHz</td>
</tr>
<tr>
<td>Total number of available RBs, ( N_{RB} )</td>
<td>50</td>
</tr>
<tr>
<td>RB bandwidth, ( W_{RB} )</td>
<td>180 kHz</td>
</tr>
<tr>
<td>Thermal noise, ( \eta )</td>
<td>(-174) dBm/Hz</td>
</tr>
<tr>
<td>eNB transmit power per RB per sector, ( P_{eNB} )</td>
<td>29 dBm</td>
</tr>
<tr>
<td>HeNB transmit power per RB, ( P_{HeNB} )</td>
<td>3 dBm</td>
</tr>
<tr>
<td>eNB antenna gain</td>
<td>14 dBi</td>
</tr>
<tr>
<td>Sectors per eNB</td>
<td>3</td>
</tr>
<tr>
<td>Minimum distance between macro UE and eNB</td>
<td>35 m</td>
</tr>
<tr>
<td>Minimum distance between femto UE and HeNB</td>
<td>0.2 m</td>
</tr>
<tr>
<td>Number of macro/femto UE Rx antennas</td>
<td>2 Rx</td>
</tr>
<tr>
<td>Wall penetration loss, ( L_{tw} )</td>
<td>20 dB</td>
</tr>
<tr>
<td>Interference threshold, ( I_{th} )</td>
<td>(-72, -87) dBm</td>
</tr>
<tr>
<td>Subframe time duration, ( t_s )</td>
<td>1 ms</td>
</tr>
</tbody>
</table>

**Table 6.3: Simulation Parameters.**

Fig. 6.5 demonstrates the need for femto-to-macro interference coordination and the benefit of resource partitioning. This figure shows the CDFs of DL interference only for affected macro UEs in a system consisting of four apartment blocks and ten macro UEs per macro-cell sector, with and without resource partitioning. An interference threshold of \( I_{th} = -72\) dBm, \( i.e., G_{th} = -75\) dB is used. For comparison purposes, a third CDF is displayed showing the interference only from the macro layer, \( i.e., \) HeNB transmit powers are reduced to zero, keeping the allocation of resources unchanged. This third case represents the ideal situation where there is no interference from the femto layer since priority is assumed to lie with macro UEs. The performance of any scheme to mitigate DL interference for affected macro UEs must approach the performance of this ideal case. It is clear from the figure that resource partitioning...
reduces the interference by approximately 10 dB at the 50th percentile. Furthermore, it is seen that resource partitioning approaches the performance of the ideal case particularly in the high interference regime, where the offending HeNBs suppress transmission on the vulnerable RBs. The difference between the lower interference regimes of the curve with resource partitioning and the case without femto interference indicates the amount of additional interference caused by HeNBs that do not perform resource partitioning because they do not lie in the vicinity of any vulnerable macro UEs. Therefore, it is clear from this figure that there is a significant benefit to be made from resource partitioning. The rest of the figures show the effect of resource partitioning on the macro and femto performance.

The capacity performances of combined macro and femto-cell UEs depicted in Figs. 6.6 through 6.9 are compared against a benchmark system that emulates a state-of-the-art cellular network. In this benchmark system, no HeNBs exist, i.e., all UEs previously classified as femto UEs are served by the outdoor eNBs. All UEs in the benchmark system are therefore macro UEs and must share the available macro resources.

Fig. 6.6 shows the overall DL macro user capacity for 4 and 14 grids with 10 macro UEs per macro-cell sector and for $I_{th} = -72$ and $-87$ dBm. The two $I_{th}$ values are chosen in particular because they represent two extreme cases: one in which the exclusion region is small enough...
Femto-cell Downlink Resource Partitioning

Figure 6.6: CDFs of the overall DL macro user capacity for a system with and without resource partitioning, compared against the benchmark system with no femto-cell deployment.

... to cause approximately 13% of HeNBs to partition resources ($I_{th} = -72$ dBm) and the other (-87 dBm) where the exclusion region is large enough to cause approximately 76% of HeNBs to partition resources. For this figure, capacity statistics are collected from all macro UEs, regardless of whether they lie outdoors or indoors and regardless of whether they are vulnerable to heavy HeNB interference or not. It is observed that when resource partitioning is applied, a consistent gain is achieved over the case where no resource partitioning is used, i.e., both macro and femto-cells fully utilise all available resources. Fig. 6.6 reveals that there is a higher resource partitioning gain in the lower capacity regime (lower percentiles of the CDF). This is due to affected macro UEs that severely suffer from interference originating from nearby HeNBs. In the higher capacity regime, resource partitioning gains diminish, since macro UEs achieving high capacities typically lie outdoors, well protected from interfering HeNBs through walls, so that the dominant interference for such macro UEs originates from other eNBs, a situation which resource partitioning does not address. It is observed that the performance of the system with 14 grids per macro-cell sector shown in Fig. 6.6(b) is consistently worse than the performance of the system with the lower grid density, shown in Fig. 6.6(a). This is expected, as increasing the grid density increases the amount of interference originating from the femto layer. For the benchmark, a higher grid density means that the same amount of resources in the macro-cell have to be shared among a higher number of users, thus compromising user capacity. Interestingly, it is observed that when $I_{th} = -87$ dBm, the performance of the systems with either grid density are almost identical. This is attributed to the fact that in either case, the...
number of macro UEs remains the same, and the high value of $I_{th}$ then ensures that the majority of HeNBs partition resources. As a result, the amount of femto interference stays largely independent of the grid density. Of note is the fact that a decreasing $I_{th}$ enhances the attainable gains in macro UE capacity. It is clear from Fig. 6.6 that augmenting a cellular network with femto-cells yields tremendous capacity gains over the benchmark system. These gains are attributed to two reasons. First, in the benchmark system, all former femto UEs are served by the outdoor eNB, where high wall penetration losses result in a highly attenuated signal. The second reason is that in the benchmark system, all UEs must share the macro resources, so that each UE is assigned fewer RBs compared to the case with femto-cell deployment. For four apartment blocks per sector, Fig. 6.6(a), with each apartment having a 10% probability of containing an active HeNB, each sector contains, on average, ten femto UEs in addition to the ten macro UEs. This means that in the benchmark system, each macro UE, on average, is allocated half the number of RBs in comparison to the system with femto-cell deployment. Therefore, in the benchmark system, the spatial reuse gain that is made available through femto-cell deployment is lost. The situation is obviously worsened in the 14 grid per sector case, as shown in Fig. 6.6(b). This is also responsible for the benchmark system showing the highest outage. In this context, a UE goes into outage if the achieved SINR on all RBs is less than $\gamma_{\text{min}}$. Finally, in the very low capacity regime ($< 0.1 \text{ Mbps}$ in either case), the benchmark system outperforms the system without resource partitioning. This is due to excessive femto-to-macro interference experienced by macro UEs trapped within the coverage area of femto-cells.

Fig. 6.7 shows the overall femto user capacity on the DL. Results are gathered for all femto UEs, regardless of whether they are in the vicinity of a vulnerable macro UE or not. In general, very high capacities are achieved within femto-cells. This is due to the very short transmission distances within femto-cells and outdoor interference protection through high wall penetration losses. It is observed that in all cases, user capacities saturate at 39.6 Mbps, due to the upper bound of the link-to-system mapping (6.3). According to Table 6.1 the maximum achievable spectral efficiency is capped at $\rho_{\text{max}} = 4.4 \text{ bps/Hz}$, and since HeNBs only serve one femto UE, with all available resources, $N$, being allocated to this UE, this equates to a maximum DL capacity of 39.6 Mbps. Fig. 6.7 also reveals that femto-cells must sacrifice some capacity when resource partitioning is in place. This is obvious, since the affected HeNBs are forbidden from using RBs allocated to nearby macro UEs. Moreover, the lower the threshold, $I_{th}$, the higher the partitioning of femto-cell resources, and thus, the lower the proportion of femto UEs that approach the maximum capacity. For $I_{th} = -72 \text{ dBm}$, the degradation in femto user capacity
Figure 6.7: CDFs showing overall femto DL user capacity for a system with resource partitioning compared against a system without resource partitioning.

is in the order of 1 Mbps. On the other hand, when $I_{th} = -87$ dBm, the degradation increases to approximately 10 Mbps. It is important to note that owing to the full buffer assumption, the degradation in femto user capacities reflects a worst case scenario. In case femto-cells do not utilise all available resources, the degradation due to resource partitioning is obviously expected to be lower. A trade-off between the improvement in macro capacity and degradation of femto capacity exists. Optimisation of this trade-off depends on the acceptable degradation of macro-cell capacity (see Fig. 6.6), in particular, at the low percentiles of the corresponding CDF. This enables the determination of the appropriate threshold, $I_{th}$, which in turn results in a certain degradation of femto-cell performance.

Figs. 6.8 and 6.9 concentrate on affected macro and femto UEs. Fig. 6.8 shows the capacity performance of affected macro UEs. It is observed that resource partitioning delivers a significant gain to the DL performance of affected macro UEs. It is seen that regardless of the grid density, with $I_{th} = -72$ and $-87$ dBm, a five and, respectively, ten-fold capacity increase of affected macro UEs is observed.

Fig. 6.9 shows the sacrifice in DL capacity that affected femto UEs must incur in order to enable resource partitioning. It is seen that while 35% of these UEs enjoy saturated capacities without resource partitioning, as expected, this percentage reduces when resource partitioning
Figure 6.8: CDFs showing DL user capacity only for affected macro UEs for a system with resource partitioning compared against a system without resource partitioning.

Figure 6.9: CDFs showing DL user capacity only for affected femto UEs for a system with resource partitioning compared against a system without resource partitioning.
is applied. It is observed that UEs associated with HeNBs that must partition resources incur a reduction in DL capacity of approximately 25% with $I_{th} = -72$ dBm and 39% with $I_{th} = -87$ dBm. It is important to note that for a sacrifice of 39% of femto capacity, the affected macro UEs are rewarded with a significant ten-fold capacity increase. We note that with either grid density, the affected macro and femto UE performance is almost identical because in both cases, the macro UE density remains the same and therefore, every HeNB must partition the same proportion of resources.

The sum system capacity in the DL normalised per macro sector shows some interesting trends. With a grid density of 4 grids per macro-cell sector and $I_{th} = -72$ dBm, the use of resource partitioning results in an affected macro UE capacity increase of 6.4% at the cost of a 2.8% degradation in femto capacity. However, when $I_{th} = -87$ dBm, a 14.2% increase in macro capacity is accompanied by a 29.6% decrease in femto capacity. The situation is different for the case when the grid density is increased to 14 grids per macro sector. When $I_{th} = -72$ dBm, a 15.7% increase in macro capacity is attained at the expense of a 2.8% decrease in femto capacity. For $I_{th} = -87$ dBm, resource partitioning results in a 53.2% increase in affected macro UE capacity with a 25.1% decrease in femto capacity. This shows that with decreasing grid densities, a relatively high interference threshold, $I_{th}$, becomes more effective.

6.6 Summary

It has been seen that in a closed-access system, macro UEs lying in the proximity of femto-cells experience at least as much DL interference from HeNBs as they do from eNBs. It has been demonstrated that by introducing resource partitioning, the capacity of such macro UEs can be boosted by a factor of ten. The cost incurred by femto UEs in doing so is minimal as they lose less than half of their capacity (which is already more than one order of magnitude higher than macro UE DL capacity). Femto users therefore experience a very high throughput inside femto-cells due to the favourable channel conditions and continue to do so even in the presence of resource partitioning. Introducing resource partitioning to a closed-access system with femto-cell deployment substantially boosts the sum system capacity while ensuring reliable macro-cell operation.

Finally, it needs to be mentioned that there is some delay associated with the implementation of the resource partitioning concept. Once the victim UE wanders into the coverage of an active
femto-cell, the femto-cell must first be made aware of its presence. Typically, when the UE detects a stronger eNB than its serving one, it will send measurement reports to the serving eNB in order to request a handover. The source (serving) and target eNBs then negotiate the handover. In the case of CSG femto-cells, the unregistered UE cannot handover to the HeNB. However, by this stage, the HeNB is aware of the presence of the victim macro UE. However, this is obviously not instantaneous due to the delays present on the wired interfaces between the eNB and the HeNB and the processing times at both ends. Furthermore, the resource allocation in LTE can change from subframe to subframe. Therefore, the HeNB needs to be kept informed at all times of the resource allocation of the trapped macro UE. Typically, the earliest the HeNB can partition resources is on the subframe after it receives the information. Therefore, such matters related to delay and complexity are subject to further research.
Conclusions, Limitations and Future Work

7.1 Summary and Conclusions

Chapter 2 begins by presenting an evolution of cellular networks from the very first mobile networks deployed in the 1950s to Long-Term Evolution (LTE) systems and beyond. Next, attention is diverted to presenting the key concepts that are used repeatedly in the remaining chapters. In connection with this, first the concept of Shannon capacity is introduced. This section also revises methods by which capacity on a wireless link can be increased and introduces various issues related with this, e.g., channel fading, bandwidth limitations, etc. Various duplexing and multiple access techniques are then introduced. The chapter ends by motivating the reason for the current surge in femto-cell research by introducing the femto-cell concept.

Chapter 3 discusses the deployment of a hybrid system which adds a time division duplex (TDD) component to an existing frequency division duplex (FDD) system, thereby enabling ad hoc communication to take place between the entities of a hotspot without over-burdening the base station (BS). Ad hoc communication between devices in close vicinity of one another is an envisaged characteristic of so-called home networks or femto-cells. The results presented show that this type of intra-hotspot communication can be supported through the use of the TDD underlay concept without adding any additional infrastructure to a cellular system. However, it is also apparent through these results that a clear shortcoming has been identified by intro-
Producing an additional wireless hop in a network containing clustered distributions of users. This shortcoming appears in the form of a severe capacity bottleneck on the BS-gateway UE (GUE) hop. Therefore, it is clear that deploying a femto-cell with a radio frequency (RF) backhaul to the core network (CN) does not deliver the envisaged data-rates to the indoor users. The only way to address this issue is to significantly increase the capacity of the BS-GUE link. However, given the constraint that the air interface, bandwidth, etc. must remain the same to allow for legacy user equipment (UE) operation, the only way of achieving this is to revert to a wired BS-GUE link. This then, takes the research into the realm of classical femto-cells discussed in depth in Chapter 5.

Meanwhile, a detour is taken to mathematically analyse the occurrence of a well-placed node within a typical hotspot. In Chapter 3, the GUE is chosen at random. However, in a practical implementation of the system, the GUE should be chosen such that it has a low path loss to the macro-cell BS and additionally, has good communication links with the rest of the UEs in the hotspot. Chapter 4 deals with the latter, i.e., ad hoc operation within hotspots. A mathematical treatment of hotspots in which first, the probability density function (pdf) of path loss distribution between uniformly distributed users in a circular hotspot is derived. This result is then used to derive the probability that a hotspot of a certain radius contains one or more GUEs by defining the GUE in graph theoretic terms.

Chapter 5 begins by formally introducing femto-cells and discussing various issues associated with their deployment within cellular networks. A performance analysis of different deployment configurations is then presented and the results are compared against those of a traditional, state-of-the-art cellular network. It is shown that femto-cell deployment poses a viable complement to cellular networks. A cellular network stands to significantly gain in overall system throughput through the widespread deployment of home evolved NodeBs (HeNBs). Not only do these HeNBs improve indoor coverage, bringing wireless broadband-like experience directly to indoor environments, but they also offload resources from the evolved NodeB (eNB), which can be utilised to improve coverage to outdoor users. However, if a macro UE lies within a closed-access femto-cell, it might not be able to receive a downlink (DL) transmission from its eNB because of high signal attenuation and, more importantly, very high interference from the nearby HeNB. If a closed-access femto-cell happens to contain a macro UE, there has to be a method of nullifying the DL interference experienced by this macro UE or else it will almost certainly go into outage.
Chapter 6 closely studies this issue, i.e., femto-to-macro DL interference in systems with closed-access femto-cells deployed. A novel interference mitigation technique is proposed to control this particular interference scenario and extensive system-level simulations show the effectiveness of the proposed approach. It is demonstrated that by introducing resource partitioning, the capacity of trapped macro UEs can be boosted by a factor of ten. The cost incurred by femto UEs in doing so is minimal. Femto users therefore experience a very high throughput inside femto-cells due to the favourable channel conditions and continue to do so even in the presence of resource partitioning. Introducing resource partitioning to a closed-access system with femto-cell deployment substantially boosts the sum system capacity while ensuring reliable macro-cell operation.

7.2 Limitations and Future Work

7.2.1 Femto-cell Research

The work presented in Chapters 3, 5 and 6 have all offered a holistic insight into the benefits of deploying femto-cellular structures within an established cellular network. However, all of these studies employ random resource allocation, i.e., resources are not allocated based on the actual channel conditions that a user is currently experiencing. This rather simplistic approach, therefore, does not aim to maximise capacity through smart scheduling. Furthermore, scheduling is expected to play a big part in delivering satisfactory cell-edge performance as per the LTE goals described in [14]. Therefore, future iterations of this work are expected to have a clever scheduling component.

Next, all the system-level simulations have been performed for a full-buffer traffic model. However, in order to make the results more accurate, a more realistic traffic model should be employed in future research. With a realistic traffic model, the loss in capacity through resource partitioning is expected to be even less, since there would be no necessity for a HeNB to transmit on all resources if a certain capacity target is already met or if there is no data to transmit.

Finally, most importantly, in all of these simulations, it has been assumed that there is no interference on the control channels. In a realistic system, this is not the case — more so when co-channel femto-cells are embedded within macro-cells. Fig. 7.1 illustrates the extra amount of interference introduced by embedded co-channel femto-cells.
Conclusions, Limitations and Future Work

Figure 7.1: Embedded femto-cells inject significant amounts of additional signalling interference to the system.

It is important for future research to concentrate on assessing the amount of additional interference caused by femto-cell deployment and proposing methods to control it. In LTE, in order to support the transmission of DL and uplink (UL) transport channels, there is a need for DL signalling. The signalling consists of DL scheduling assignments including information required for the UE to properly receive, demodulate and decode the downlink shared channel (DL-SCH), UL scheduling grants informing the UE about the resource blocks (RBs) and transport format to use for the UL transmission and hybrid-automatic repeat request (ARQ) acknowledgments in response to uplink shared channel (UL-SCH) transmissions [9, 14]. Therefore, it is important that the signalling be received with satisfactory quality. If the signalling cannot be correctly decoded, the rest of the transmission fails. As shown in Fig. 7.2, the control signalling is transmitted in the first part of each subframe. Thus, each subframe consists of a control and a data region. For design simplicity, the control region occupies between 1 and 3 orthogonal frequency division multiplexing (OFDM) symbols [9, 14]. The size of the control region is directly proportional to the number of users being served. The control signalling consists of three different physical channel types:

- The physical control format indicator channel (PCFICH) informs the UE about the size
of the control region, i.e., the number of OFDM symbols used. Each cell contains only one PCFICH.

- The physical downlink control channel (PDCCH) signals DL scheduling assignments and UL scheduling grants. There are typically multiple PDCCHs in a cell.

- The physical hybrid-ARQ indicator channel (PHICH) is used to signal hybrid-ARQ acknowledgments in response to UL-SCH transmissions. Again, there are multiple PHICHs in a cell.

Of these three, the PCFICH is the most vital because if this is incorrectly decoded, that subframe is completely wasted, since the UE is then unaware of the starting point of the data region. Fig. 7.2 also shows the positions of reference signals. Reference signals are used to carry out coherent demodulation of the different physical channels and also for the UE to estimate the DL channel [9, 14]. For more details on control signalling in LTE, the reader is urged to refer to [9, 14].

A brief study has been carried out to gain an initial understanding of the amount of interference added to the system by femto-cells. The simulation is carried out over just one resource element (RE). It is assumed that this RE corresponds to one PCFICH element. Although LTE provides redundancy so that even if one part of the spectrum is particularly badly affected, another may have good channel conditions for satisfactory decoding of the PCFICH, this is not taken into account here. UEs, eNBs and HeNBs are distributed in a tiered system exactly as described in Chapter 6. The same channel models are used and the signal-to-interference-plus-noise ratio (SINR) on the single RE is calculated and its cumulative distribution function (CDF) reported. The parameters shown in Table 7.1 are used. It is seen that all the parameters remain

![Figure 7.2: Control and data regions within an LTE subframe. Reference symbols are distributed over both RBs.](image)
Table 7.1: Simulation Parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average 5x5 apartment blocks per macro-cell sector</td>
<td>4, 6, 8, 10, 12 &amp; 14</td>
</tr>
<tr>
<td>Average macro UEs per macro-cell sector</td>
<td>10</td>
</tr>
<tr>
<td>Inter-site distance</td>
<td>500 m</td>
</tr>
<tr>
<td>Individual apartment dimensions</td>
<td>10 m x 10 m</td>
</tr>
<tr>
<td>HeNB deployment probability, $p_1$</td>
<td>0.2</td>
</tr>
<tr>
<td>HeNB activation probability, $p_2$</td>
<td>0.5</td>
</tr>
<tr>
<td>Femto UEs per active femto-cell</td>
<td>1</td>
</tr>
<tr>
<td>Avg. femto UEs per macro-cell sector</td>
<td>10</td>
</tr>
<tr>
<td>RB bandwidth</td>
<td>180 kHz</td>
</tr>
<tr>
<td>Thermal noise</td>
<td>$-174 \text{ dBm/Hz}$</td>
</tr>
<tr>
<td>eNB transmit power</td>
<td>0 dBm</td>
</tr>
<tr>
<td>HeNB transmit power</td>
<td>$-3 \text{ dBm}, 0 \text{ dBm}$</td>
</tr>
<tr>
<td>eNB antenna gain</td>
<td>14 dBi</td>
</tr>
<tr>
<td>Minimum distance between macro UE and eNB</td>
<td>35 m</td>
</tr>
<tr>
<td>Minimum distance between femto UE and HeNB</td>
<td>20 cm</td>
</tr>
<tr>
<td>Number of HeNB/eNB Rx antennae</td>
<td>2 Rx</td>
</tr>
<tr>
<td>Number of macro/femto UE Rx antennae</td>
<td>2 Rx</td>
</tr>
<tr>
<td>Wall penetration loss</td>
<td>20 dB</td>
</tr>
</tbody>
</table>

the same except for the $5 \times 5$ grid density and H/eNB transmit powers. The choice of transmit power on the control channel is variable and can be adjusted by the operator. In this simple study, the H/eNB transmit powers are first kept the same at 0 dBm, each and next, the HeNB transmit power is reduced by 3 dB. This rather strict constraint is imposed so as to carry out a worst-case performance analysis. The study is conducted for various grid densities so as to assess their impact on the interference.

Fig. 7.3 shows the achieved DL SINRs. According to [137], an SINR of at least -1.7 dB is required for proper decoding of the control channels. Therefore, the figure contains an indication of where the curves are in relation to this threshold. It is evident from this figure that in the absence of femto-cells, around 93% of UEs attain the required SINR. However, the situation changes dramatically when femto-cells are introduced and becomes worse as their density is increased. As expected, lowering the HeNB transmit power improves the SINR but even in the
best case, approximately 45% of UEs do not achieve the required SINR, which is unacceptable. Again, it must be stressed that these pessimistic results do not accurately reflect reality, but are produced here to give the reader a rough estimate of how interference is increased when femto-cells are deployed.

![Figure 7.3: SINRs for all macro UEs for varying grid densities. A higher grid density lowers SINRs as expected.](image)

Fig. 7.4 addresses the same question from the perspective of femto UEs. In this case, due to extremely good channel conditions within the femto-cell, it is observed that the grid density does not significantly affect the achieved DL SINRs. Even though the performance degrades with an increasing grid density, in all the cases, over 95% of the UEs achieve the required SINR for proper demodulation of the control channel.

While this simple study exaggerates the amount of interference expected on the control channel with femto-cell deployment, it gives a rough indication that this is an issue that is certainly subject to further investigation.

It has been shown in Chapter 5 that from the macro UE’s viewpoint in closed-access systems, the DL direction is the critical traffic direction. Similarly, from the femto UE’s viewpoint in closed-access systems, the UL direction is critical. Therefore, depending on whether priority lies with the macro or femto-cell, research on closed-access systems must be devoted to mitigate UL interference imposed on HeNBs, or DL interference caused by closed-access HeNBs.
Finally, the performance evaluation shown in this thesis can be solidified by performing a further study on the tradeoff between the benefits shown here and the additional overhead, delay and complexity that the system must endure. This is a critical area of future research on this topic.

7.2.2 Star-node Research

In Chapter 4, the probability of the existence of star-nodes is investigated. In order to approach this problem, random graph theory [106] has been made use of. A random graph is obtained by starting with a set of \( n \) vertices and adding edges between them at random. The probability of the existence of an edge is defined \textit{a priori} and applies to all edges. If a real network were to be considered as a graph, with each user considered a node and an edge representing a viable link between nodes, the probability of an edge existing between two nodes is higher the closer the nodes are to one another, since it is expected that the path loss between them generally decreases as the distance also decreases. Random graph theory is not capable of achieving this and therefore, the results presented in this chapter are good approximations but not exact matches. In order to improve the accuracy of the results, random geometric graph theory [107] may be used. In random geometric graphs, the probability of an edge existing between two nodes is dependent on the distance between them. Therefore, research into the existence of
star-nodes based on random geometric graph theory is worthy of further investigation.
Derivation of the pdf of Path Loss Distribution in a Circle

This appendix presents a derivation of the probability density function (pdf) of path loss distribution between nodes uniformly distributed in a circular hotspot of radius $R_h$. From Section 4.2.2, it has been shown that the path loss between two points separated by $X d_0$ meters is written as

$$L = a + b \log_{10}(X) + \xi,$$  \hspace{1cm} (A.1)

where $X = d/d_0$. Furthermore, for a circle of radius $R_h$ having uniform node distribution, it is known that the pdf of the distance of any point from the centre, $x$, is

$$f_X(x) = \frac{2x}{R_h^2}, \quad x \in [0, R_h].$$  \hspace{1cm} (A.2)

The angular distribution is uniform on $[0, 2\pi]$. Deriving the pdf of $L$ involves the addition of two random variables and a constant. First we find the pdf of the random variable $Y = b \log_{10} X$ using the transformation of random variables. Thus,

$$f_Y(y) = \frac{2 (\ln 10) 10^{2y/b}}{b R_h^2}, \quad y \in (-\infty, b \log_{10} R_h].$$  \hspace{1cm} (A.3)
Next, we calculate the pdf of \( Z = b \log_{10} X + W \). The pdf of \( W \) is known to be

\[
f_W(w) = \frac{1}{\sigma \sqrt{2\pi}} \exp \left( -\frac{w^2}{2\sigma^2} \right).
\]  

(A.4)

Since this is an addition of two independent random variables (\( Y \) and \( W \)), we can use the convolution integral to find the pdf of \( Z \), i.e., \( f_Z(z) = f_Y(y) * f_W(w) \) (where \(*\) is the convolution operator).

\[
f_Z(z) = \int_{-\infty}^{\infty} f_W(w) f_Y(z-w) \, dw
\]

\[
= \frac{2(\ln 10)}{\sqrt{2\pi} \sigma b R_h^2} \int_{A}^{\infty} \exp \left( -\frac{w^2}{2\sigma^2} \right) 10^{2(z-w)/b} \, dw
\]

\[
= \frac{2(\ln 10)}{\sqrt{2\pi} \sigma b R_h^2} \exp \left\{ \frac{2b (\ln 10) z + 2\sigma^2 (\ln 10)^2}{b^2} \right\}
\]

\[
\times \int_{A}^{\infty} \exp \left\{ -\frac{\left( w + \frac{2\sigma^2(\ln 10)}{b} \right)}{2\sigma^2} \right\} \, dw,
\]

(A.5)

where \( A = z - b \log_{10} R_h \). Let \( k = w + \frac{2\sigma^2(\ln 10)}{b} \). Using this in (A.5),

\[
f_Z(z) = \frac{2(\ln 10)}{\sqrt{2\pi} \sigma b R_h^2} \exp \left\{ \frac{2b (\ln 10) z + 2\sigma^2 (\ln 10)^2}{b^2} \right\}
\]

\[
\times \int_{B}^{\infty} \exp \left\{ -\frac{k^2}{2\sigma^2} \right\} \, dk,
\]

(A.6)

where \( B = z - b \log_{10} R_h + \frac{2\sigma^2(\ln 10)}{b} \). Let \( l = \frac{k}{\sqrt{2\sigma}} \). Decomposing the integral into the standard form of the error function,
Derivation of the pdf of Path Loss Distribution in a Circle

\[ f_Z(z) = \frac{2(\ln 10)}{\sqrt{2\pi}\sigma b R_h^2} \exp \left\{ \frac{2b (\ln 10) z + 2\sigma^2 (\ln 10)^2}{b^2} \right\} \times \int_C \exp \left\{ -l^2 \right\} \sqrt{2\sigma} \, dl, \]

(A.7)

where \( C = \frac{z}{\sqrt{2}\sigma} - \frac{b \log_{10} R_h}{\sqrt{2}\sigma} + \frac{\sqrt{2}\sigma (\ln 10)}{b} \). Using the definition of the error function as follows:

\[ \text{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} \, dt, \]

we get

\[ f_Z(z) = \frac{(\ln 10)}{b R_h} \exp \left\{ \frac{2b (\ln 10) z + 2\sigma^2 (\ln 10)^2}{b^2} \right\} \times \{1 - \text{erf} (C)\}. \]

(A.8)

Finally, we solve for the pdf of

\[ L = a + b \log_{10} X + Z \]

This final step translates to a shift and the pdf of \( L \) is given as

\[ f_L(\ell) = \frac{(\ln 10)}{b R_h^2} \exp \left\{ \frac{2b (\ln 10) (\ell - a) + 2\sigma^2 (\ln 10)^2}{b^2} \right\} \times \{1 - \text{erf} (D)\}; \forall \ell, \]

(A.9)

where

\[ D = \frac{\ell b - a b - b^2 \log_{10} R_h + 2\sigma^2 (\ln 10)}{\sqrt{2b}\sigma}. \]

(A.9) gives the pdf of path loss distribution in a circular scenario of radius \( R_h \) as seen from the centre of the circle. Using an alternate expression for the error function as shown in [138],
(A.9) can be written as

\[
\frac{(\ln 10)}{bR_h^2} \exp \left\{ \frac{2b (\ln 10) (\ell - a) + 2\sigma^2 (\ln 10)^2}{b^2} \right\} \times \left\{ \frac{2}{\pi} - \frac{2}{\pi} \int_0^{\pi/2} \exp \left[ -\frac{2D^2}{2 \sin^2 \theta} \right] \sin \theta \, d\theta \right\} \, \text{sgn} (D) \right\}; \forall \ell, \tag{A.10}
\]

where \( D \) holds the same meaning as defined above and \( \text{sgn}(\cdot) \) is the signum function.
Appendix B

List of Publications

This section contains a list of papers either accepted for publication, pending publication or submitted for publication.

B.1 Published


**B.2 Accepted**


**B.3 3GPP Standardisation Contributions**


**B.4 Patents**


Selected Publications

This chapter contains all work either already published or submitted for publication.
Application of the TDD Underlay Concept to Home NodeB Scenario

Zubin Bharucha and Harald Haas
Institute for Digital Communications
University of Edinburgh
Edinburgh EH9 3JL, UK
Email: {z.bharucha,h.haas}@ed.ac.uk

Abstract—This paper presents a spectrum sharing approach which exploits the clustered distribution of users as would be expected in a typical home with several communicating devices (also known as a femto-cell) or in public places such as airports, malls, etc. From each cluster, a mobile station (MS), known as a gateway mobile (GM), acts as a relay between the other users of the cluster and the base station (BS) of the associated cell. The system makes use of frequency division duplexing (FDD) for communication between the BS and the GM. Traffic is assumed to be asymmetric in favour of downlink (DL) due to current trends in user traffic requirements. The unused resource in the uplink band are then used for communication within the cluster using time division duplexing (TDD) underlay. This model is compared against one in which the same user distribution is assigned but the GM concept is not made use of i.e. an FDD system based on the results, it has been shown that the proposed enhancements lead to a significant increase in system spectral efficiency through the use of intra-cluster communication.

I. INTRODUCTION

Due to the poor spectrum utilisation in current wireless networks, a system in which unused resources are exploited is presented as a step towards future wireless network solutions which are envisaged to be characterised by the lack of frequency planning. Dynamic self-organising and spectrum-sharing networks using picocellular structures are considered as improvements to the current wireless network solutions which do not efficiently utilise the available bandwidth [2], [3].

Ad hoc solutions to cellular networks are becoming more popular. However, all the proposals presented in [4]–[6] either require additional infrastructure to be installed in the system or require complex computations in order to find a suitable route.

Next generation wireless networks face challenges in the form of a highly increased number of users, increased traffic generated by each user and traffic asymmetry in the downlink. Duplexing and resource allocation are two of the critical issues in the design of next generation systems. An air-interface for next generation systems must be efficient and flexible in the utilisation of spectrum and must be able to dynamically allocate resources and exploit multi-user diversity. The hybrid division duplex (HDD) architecture [7] aims to combine the advantages of FDD and TDD schemes to increase the flexibility and efficiency of a mobile communication network. Cell partitioning ensures that nomadic users are provided with high data-rates and asymmetric service through TDD, and high-speed users are given reliable service using FDD. However cell partitioning/sectoring does not solve the detrimental BS

BS interference which affects cellular TDD systems. Thus, an ideal solution is one that does not explicitly make use of cell partitioning and that is not computationally complex.

FDD, in the classical sense (one frequency band for UL traffic and another for DL), does not effectively support channel asymmetry. TDD, on the other hand, is very well suited to support asymmetry since time resources can be distributed as per the asymmetry demands. Asymmetry in favour of DL results in an under-usage of the FDD UL band [8]. The idea presented in this work introduces an FDD-TDD switching point in the undersused FDD band after which TDD is used to carry intra-cluster load, thus, the FDD and TDD modes are combined in a soft manner.

Let a transmission slot be defined by a certain time duration and frequency allocation. A transmission slot can be considered as the basic building block of a duplex communication system. A series of alternating transmission slots (one transmission slot for UL and the next for DL) at different time instances but at the same frequency results in a pure TDD system. Two clumps of simultaneous transmission slots in opposing directions, one at a particular frequency and the other clump at a different frequency result in a pure FDD system. Introducing an FDD-TDD switching point in one of the frequency bands results in an FDD system before the switching point, a TDD system after the switching point and a simple/broadcast transmission system in the other FDD band after the switching point. Fig. 1 makes this concept clearer. This, then, presents an efficient and elegant method of dealing with asymmetric traffic demands of users.

Fig. 1: A pure FDD system can be considered as two TDD systems without switching points. By eliminating the latter restriction, a whole class of new system designs are possible. Thereby, the advantages of both duplex modes can be exploited constructively while the disadvantages of each mode can be circumvented.
There is an increasing amount of research devoted to 3G femtocells and home base stations [9] which are envisaged to reduce the load on macrocell BSs and improve quality of service to indoor users. The usefulness of this scheme to femtocell research is apparent due to the fact that no additional infrastructure or change in the air interface is needed.

Home networks are characterised by intercommunicating devices. A traditional FDD cellular system is incapable of supporting ad hoc communication between the entities of a cluster since all communication must be directed via the BS. The introduction of the TDD mode in the lesser used band enables ad hoc communication to take place within the cluster without over-burdening the BS.

The remainder of the paper is organised as follows. GM selection, frame structure, path loss and interference models are described in Section II. The simulation model is described in Section III. The metrics on which the system performance is evaluated are described in Section IV. The results are presented in Section V. Finally, Section VI includes concluding remarks and further work.

II. SYSTEM SETUP

A. Gateway Mobile

Practically, for the cluster to be formed, the MSs need to be aware of one another. One method of doing this is by making use of the receiver-initiated, time-multiplexed busy tone concept as described in [10], i.e., if the busy tone received by the GM of a cluster from a MS is above a predefined threshold, it belongs to the cluster.

One MS from each cluster of users is selected as a GM which relays traffic between the rest of the cluster and the BS (see Fig. 2).

Fig. 2: Part of a cell showing one cluster. The GM acts as a relay between the BS and the other MSs in the cluster.

Introducing an additional hop in the system reduces the number of entities communicating with the BS since only one entity per cluster communicates with the BS, which leaves more resources for allocation per GM. Also, since transmission distances are reduced, higher signal-to-noise ratios (SNR) are available, leading to increased data rates (especially within the cluster) through the use of higher order modulation schemes.

B. Frame Structure

Due to trends in user traffic requirements, it is assumed that all traffic in the system is asymmetric in favour of downlink. Therefore, the proposed frame structure allows for channel asymmetry in favour of DL. The unused resources in the FDD UL band are used for intra-cluster communication in the TDD mode.

The frame structure is as shown in Fig. 3. A frame consists of two chunks (a chunk is the basic time-frequency unit for resource allocation), each of which consist of 12 OFDM symbols and 8 subcarriers. Since each chunk occupies a bandwidth of 312.5 kHz, the entire 50 MHz bandwidth (in UL and DL, each) can accommodate 160 chunks (512 subcarriers) with a subcarrier spacing of 39.0625 kHz. However, only 144 are available for use as the available bandwidth is 45 MHz (the rest being used up for guard bands) [11].

![Frame Structure Diagram]

Fig. 3: The DL and UL frames, each with 2 chunks.

The entire DL band is dedicated to BS -> GM communication. In the UL band, in each frame, the first timeslot (TS) (with 144 chunks in the frequency domain) is reserved for GM -> BS communication and the second TS (again with 144 chunks) can either be used for GM -> MS or MS -> GM communication.

For the benchmark system, the same frame structure is used but without the TDD underlay. Therefore, the entire DL band is used for BS -> MS communication and the entire UL band is used for MS -> BS communication, thus resulting in a pure FDD system. Thus, in this case, the system does not provide support for asymmetric traffic and communication takes place over one hop.

C. Path Loss Model and Log-Normal Shadowing

For path loss calculations, WINNER path loss models are used [12]. Scenario C5 (metro, bad urban macro-cell) is used for the macro-cell and scenario B3 (indoor hotspot) is used for the femto-cell (within the clusters). In both cases, the non-line-of-sight equations are used in order to provide for the worst case scenario in terms of the desired link. The path loss models are of the form (obtained from [12])

$$PL[dB] = A\log_{10}(d[m]) + B + C\log_{10}\left(\frac{f[GHz]}{5}\right) + X,$$

(1)
where $A$, $B$, and $C$ are constants depending on the model used, $f_c$ is the centre frequency depending on which band is being considered (this information is shown in Table 1) and $X$ is a normally distributed random variable with zero mean representing the shadowing component. For the B3 path loss model, $A = 37.8$, $B = 36.5$, $C = 23$ and standard deviation of the shadowing component $\sigma = 4$ dB. For the C3 path loss model, $A = 35.74$, $B = 42.4$, $C = 23$ and standard deviation of the shadowing component $\sigma = 6$ dB. It is ensured that the path loss between any two points does not fall below the free space path loss which is calculated using

$$PL_{\text{free}}[dB] = 20 \log_{10}(d[m]) + 46.6 + 20 \log_{10}\left(\frac{f_c[GHz]}{5}\right).$$

In order to mimic realistic shadowing, a correlated log-normal fading model is implemented. Due to the slow fading process versus distance, adjacent fading values are correlated. The correlation in shadowing between two points separated by a distance $\Delta d$ m is given by

$$R(\Delta d) = \exp\left(-\frac{\Delta d}{d_{\text{corr}}} \ln 2\right),$$

where $d_{\text{corr}}$ is the decorrelation distance (3 m for B3 and 50 m for C3) and represents the distance beyond which there is no correlation in shadowing [13].

D. Interference and SINR

The 144 available OFDM chunks are allocated equally to the GMs present in a cell (for UL and DL). The system does not make use of power control. Instead, each entity transmits with a fixed power, whose values are obtained from [11] (see Table 1).

Four interference scenarios exist: GM $\leftrightarrow$ BS, BS $\leftrightarrow$ GM, GM $\leftrightarrow$ MS and MS $\leftrightarrow$ GM. Since entity interference does not exist because the system is synchronized in time (crosssections do not exist), MSs of different clusters also do not interfere with another because at any given time instant, all active MSs are either transmitting or receiving.

Both co-channel interference (CCI) and multiple access interference (MAI) are considered. For the duration of the simulation, the channel is assumed to be static in time. However, frequency selective channels are simulated using Doppler shifts due to user mobility. MAI is not considered in the downlink (i.e., BS $\leftrightarrow$ GM) since perfect synchronisation between subcarriers is assumed in the downlink. MAI represents own cell interference and is modelled as the leakage from other subcarriers onto the set of subcarriers used by that particular entity. CCI represents other cell interference towards which all the subcarriers in the system contribute. Both, MAI and CCI are calculated as shown in [14].

III. SIMULATION MODEL

The cellular scenario consists of 19 hexagonal cells in two tiers. Each cell, consisting of 3 sectors, contains a BS at its centre. A two-tier scenario consisting of hexagonal cells is used in the simulation. In order to mitigate the well-known cell-boundary effect, a "dummy" fourth-tier system is generated for the same cluster density and the interfering effects of these entities are taken into account when calculating SINRs (signal-to-noise-plus-interference-ratio), thus ensuring that all users experience approximately the same amount of interference in the system.

The clustered distribution of users is simulated by uniformly distributed users within a circle. The clusters themselves are then uniformly distributed in the cellular scenario. It is assumed that for the duration of the simulation, the GM is idle, i.e., it does not receive or transmit any of its own data.

![Fig. 4: One realisation of the clustered distribution for 100 clusters, each consisting of 4 MSs and a GM. Uniformly distributed in a 2-tier scenario. The snapshot shows 3 clusters with their respective selected GMs marked by crosses. The circles around the clusters (of radius 25 m) show the area within which the MSs of a cluster can be distributed. The circles at the centre of each cluster show the locations of the BSs.](image)

Every cluster is assumed to contain 5 MSs, one of which becomes the GM (see Fig. 4). One simulation snapshot is run for the duration of 8 frames such that every MS of a cluster is allocated 1 TS for UL and another for DL. In the TDD part of each UL frame, each GM communicates (either UL or DL) with one MS from the cluster. Thus, over the duration of the snapshot, there is duplex communication between the GM and every MS in the cluster. It is assumed that the MSs are static for the duration of the snapshot since the distance covered by a MS during the snapshot (considering approximately 3 km/hr mobility) is much less than the decorrelation distance of the path loss model and the snapshot duration is much shorter than the coherence time of the channel. The distribution of users is randomised for every snapshot as are the log-normal shadowing maps.

The parameters used in the simulation are summarised in Table 1 and are obtained from [11], [12], [15]. A best-effort system is simulated, i.e., full-buffer transmissions are assumed and capacities are calculated based on the achieved SINRs.
TABLE I: Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation duration</td>
<td>5.25/6.0 ms (6 frames)</td>
</tr>
<tr>
<td>Cluster radius</td>
<td>25 m</td>
</tr>
<tr>
<td>MSs per cluster</td>
<td>5 (including GM)</td>
</tr>
<tr>
<td>Mean terrain mobility</td>
<td>3 km/h</td>
</tr>
<tr>
<td>Frequency offset</td>
<td>0% to 2%</td>
</tr>
<tr>
<td>Center frequency in UL band (GHz)</td>
<td>3.7 GHz</td>
</tr>
<tr>
<td>Center frequency in DL band (GHz)</td>
<td>3.08 GHz</td>
</tr>
<tr>
<td>Total BS Tx power</td>
<td>50.77 dBm</td>
</tr>
<tr>
<td>Total GM Tx power (to BS)</td>
<td>24 dBm</td>
</tr>
<tr>
<td>Total MS Tx power (intracell)</td>
<td>21 dBm</td>
</tr>
<tr>
<td>Total MS Tx power (intracell)</td>
<td>24 dBm</td>
</tr>
<tr>
<td>Antennas elevation gain</td>
<td>14 dB</td>
</tr>
</tbody>
</table>

IV. PERFORMANCE METRICS

The capacity (per frame) achieved on a link $k$ is calculated as shown in (4)

$$C_k = \frac{TN_k}{T_{\text{total}}W} \sum_{i=1}^{N_k} \log_2 \left( 1 + \text{SINR}_i^k \right) \tag{4}$$

where $W$ is the subcarrier bandwidth, $N_k^i$ represents the number of subcarriers allocated for link $k$, $\text{SINR}_i^k$ is the SINR achieved on the $i$-th subcarrier on the $k$-th link, $T_{\text{total}}$ represents the number of TSS used for link $k$ and $T_{\text{total}}$ is the total number of TSS used in the simulation.

The capacity gain due to intra-cluster communication is defined as the ratio of the capacity between GMs and their MSs to the capacity achieved between the BSs and MSs in the benchmark system as shown in (5)

$$G = \frac{C_{\text{GM, MS}}}{C_{\text{BS, MS}}} \tag{5}$$

where $C_{\text{GM, MS}}$ is the mean capacity between the GMs and their associated MSs and $C_{\text{BS, MS}}$ is the end-to-end capacity in the benchmark system.

The normalised system spectral efficiency is defined as the system spectral efficiency normalised by the number of cells and subcarriers available. For the benchmark, this spectral efficiency is calculated as shown in (6)

$$\text{SE}_{\text{UL}} = \frac{\sum_{i=1}^{N_{\text{BS}}} \log_2 \left( 1 + \text{SINR}_i^k \right)}{N_{\text{BS}} N_{\text{cells}}} \tag{6}$$

where $N_{\text{BS}}$ is the number of BSs in the system, $N_{\text{BS}}^i$ is the number of subcarriers allotted to the $i$-th BS, $N_{\text{cells}}$ is the total number of subcarriers available and $N_{\text{cells}}$ is the number of cells in the system.

In the proposed system, the system spectral efficiency is the sum of the spectral efficiencies achieved on the BS-GM link and the GM-MS link. This is calculated as shown in (7). Here, $N_{\text{GMs}}$ is the number of GMs in the system, $T_{\text{total}}$ is the number of TSS allocated to any BS-GM link for the simulation (this is the total number of TSS allocated for DL and UL) and $T_{\text{GM, MS}}$ is the number of TSS allocated for GM-MS communication which is 1 for either UL or DL.

$$\text{SE}_{\text{DL/UL}} = \frac{\sum_{i=1}^{N_{\text{BS}}} \log_2 \left( 1 + \text{SINR}_i^k \right) + \sum_{j=1}^{N_{\text{GMs}}} \log_2 \left( 1 + \text{SINR}_j^k \right)}{N_{\text{BS}} N_{\text{GMs}}} \tag{7}$$

V. RESULTS

Fig. 5 shows the capacity achieved on average for a GM-MS pair. At any time instant, only one entity in every cluster is active. All entities within a cluster transmit at the same power. Since the MSs within a cluster are geographically concentrated, they undergo similar shadowing on average, which leads to the interference being very similar across time slots. As a result, due to this and channel reciprocity, the UL and DL capacities show nearly identical trends. As the number of clusters is increased, due to increased interference (CD), the capacities decrease.

Fig. 6 shows the capacity gain due to intra-cluster communication as described by (5). It is seen that the capacity gain increases as the number of clusters in the system is increased. This is because the capacity gain between GMs and their MSs does not decrease as fast as the capacity between the BSs and MSs in the benchmark system as the number of clusters in the system is increased. Furthermore, it is seen that the gain in UL is higher than that in the DL. This is because the UL capacity in the benchmark system is affected by MAI which is not the case in the DL. This causes the UL capacity in the benchmark system to be lower than the DL capacity which translates to the capacity gain being higher in UL. The difference between
the UL and DL gains reduces as the number of clusters is increased, because the difference between the UL and DL capacities in the benchmark system grows smaller with an increasing user density.

Finally, Fig. 7 shows the system spectral efficiencies in the proposed and benchmark systems as described in (6) and (7). It is clearly seen that the proposed and benchmark systems display opposing trends. In the benchmark system, the spectral efficiency decreases with increasing number of clusters in the system. This is due to the fact the interference is increased with an increasing user density which causes the SINRs of the subcarriers to decrease, which eventually leads to a decrease in system spectral efficiency. The TDD underlay with intra-cluster communication results in an increase in system spectral efficiency because in this case, the spectral efficiency is the sum of spectral efficiencies on the BS-GM hop and the GM-MS hop. The SINRs on the GM-MS link are much higher compared to the BS-GM link (due to shorter transmission distances) and the entire bandwidth is used within a cluster. Therefore, an increase in the number of clusters in the system results in an increase in the system spectral efficiency.

VI. CONCLUSION AND OUTLOOK

This paper presents a method of introducing a TDD component to an FDD system, thereby enabling full-duplex communication to take place between the entities of a cluster without over-burdening the BS. Ad hoc communication between devices in close vicinity of one another is an envisaged characteristic of so-called home networks or femtocells. Results show that this type of "intra-cluster communication" can be supported through the use of the TDD underlay concept without adding any infrastructure to a cellular system.

Merging of closely situated clusters into a single cluster such that the system supports clusters with varying number of users, introduction of power control and link adaptation are areas of further research.

ACKNOWLEDGMENT

This work was supported by DFG grant HA 35702-1 as part of program SFH-4102 (Adaptability in heterogeneous networks with wireless access - AKOM).

REFERENCES

Research Letter

The Distribution of Path Losses for Uniformly Distributed Nodes in a Circle

Zubin Bharucha and Harald Haas

Institute for Digital Communications, School of Engineering and Electronics, University of Edinburgh,
EH9 3JL, Edinburgh, UK

Correspondence should be addressed to Zubin Bharucha, z.bharucha@ed.ac.uk

Received 28 January 2008; Accepted 20 March 2008

Recommended by N. Sagiás

When simulating a wireless network, users/nodes are usually assumed to be distributed uniformly in space. Path losses between nodes in a simulated network are generally calculated by determining the distance between every pair of nodes and applying a suitable path loss model as a function of this distance (power of distance with an environment-specific path loss exponent) and adding a random component to represent the lognormal shadowing. A network with N nodes consists of N(N - 1)/2 path loss values. In order to generate statistically significant results for system-level simulations, Monte Carlo simulations must be performed where the nodes are randomly distributed at the start of every run. This is a time-consuming operation which need not be carried out if the distribution of path losses between the nodes is known. The probability density function (pdf) of the path loss between the centre of a circle and a node distributed uniformly within the circle is derived in this work.

Copyright © 2008 Z. Bharucha and H. Haas. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

1. Introduction

System-level computer simulations of wireless, mobile networks are commonplace in current research in the wireless communications field. Users are often times uniformly distributed in hexagonal cells in a system simulation. In order to find the signal-to-interference-and-noise ratio (SINR) on any link, path loss information must be known between the two communicating entities as well as the entity in question and all other potential interfering entities. Various empirically obtained path loss models exist which simulate varying propagation environments as shown in [1–4]. In [5], the authors derive the probability density function (pdf) of the distance between two nodes within communication range of one another (based on the path loss between them). This is then extended to calculating the number of communicable nodes in the vicinity of the node in question. However, to the best of the authors’ knowledge, no work has been done to analytically model the distribution of path losses between uniformly distributed nodes in a network (irrespective of whether they can sustain communication between one another or not).

Calculating the path loss between the nodes in a cellular system is usually done by actually distributing the nodes uniformly, calculating the distances between them and applying an appropriate path loss model to these distances. This must be repeated many times in order to get a statistically significant result. This operation is computationally expensive and simulation runtimes can be drastically reduced if this step could be skipped. In order to do so, knowledge of the distribution of path losses between uniformly distributed nodes in a hexagon is essential.

In this letter, the pdf of the distribution of path losses between the centre of a circle and uniformly distributed nodes within it is derived. This novel derivation can be used to find the distribution of a whole class of path loss models. A circular scenario is preferred over a hexagonal one because the derivation of the aforementioned pdf is straightforward for the circular case. Furthermore, it is also shown in this paper that the theory derived for a circular scenario agrees with the simulations for the hexagonal case very closely and is therefore a very good approximation.

The derivation of the pdf is shown in Section 2. The comparisons between theory and simulation and discussions
thereof are shown in Section 3. Section 4 contains concluding remarks.

2. Distribution of Path Losses for Uniformly Distributed Users in a Circle

Path loss is generally represented as some power of distance, $y$, plus a random variation about this power law due to shadowing [1]. Beyond some close-in distance $d_\text{b}$, the path loss (in dB) can be written as

\[ L = a + 10 \log_{10}(\frac{d}{d_\text{b}}) + \xi, \quad d \geq d_\text{b} \]  

(1)

where $a$ is an intercept which is the free-space path loss at distance $d_\text{b}$, $d$ is the distance between the two points, and $\xi$ is the shadow fading variation about the linear relationship in the log domain and is a zero-mean, normally distributed random variable with standard deviation $\sigma$, that is, $N(0, \sigma^2)$. For the sake of convenience, in (1), we make the substitutions $b = 10y$ and $X = d/d_\text{b}$. Thus, the path loss between two points separated by $Xd_\text{b}$ meters is written as

\[ L = a + b \log_{10}(X) + \xi. \]  

(2)

For a circle of radius $R$ having uniform node distribution, it is known that the pdf of the distance of any point from the center, $x$, is [6]

\[ f_x(x) = \frac{2x}{R^2}, \quad x \in [0, R]. \]  

(3)

The angular distribution is uniform on $[0, 2\pi]$. Deriving the pdf of $L$ involves the addition of two random variables and a constant. First we find the pdf of the random variable $Y = b \log_{10}(X)$ using the transformation of random variables. Thus,

\[ f_Y(y) = \frac{(\ln 10)b}{b^y} \exp \left( -\frac{y^2}{2\sigma^2} \right), \quad y \in (-\infty, b \log_{10}(R)]. \]  

(4)

Next, we calculate the pdf of $W = \frac{X}{\sqrt{X^2 + \frac{\sigma^2}{b^2}}}$.

The pdf of $W$ is known to be

\[ f_W(w) = \frac{1}{\sigma \sqrt{2\pi}} \exp \left( -\frac{w^2}{2\sigma^2} \right). \]  

(5)

Since this is an addition of two independent random variables ($Y$ and $W$), we can use the convolution integral to find the pdf of $Z$, that is, $f_Z(z) = f_Y(y) * f_W(w)$ (where $*$ is the convolution operator):

\[ f_Z(z) = \int_0^\infty f_Y(y) f_W(z-y) dy \]

\[ = \frac{(\ln 10)}{b^2 \log_{10}(R)} \int_0^\infty \exp \left( -\frac{y^2}{2\sigma^2} \right)(z-y)^2 \frac{1}{2\pi} \exp \left( -\frac{(z-y)^2}{2\sigma^2} \right) dy \]

\[ = \frac{(\ln 10)}{b^2 \log_{10}(R)} \exp \left( \frac{2(\ln 10)y + 2\sigma^2(\ln 10)^2}{b^2} \right) \]

\[ \times \int_0^\infty \exp \left( -\frac{w + (2\sigma^2(\ln 10)/b)^2}{2\sigma^2} \right) dw, \]

(7)

where $A = z - b \log_{10}(R)$. Let $k = w + (2\sigma^2(\ln 10)/b$. Using this in (7), then

\[ f_Z(z) = \frac{(\ln 10)}{b^2 \log_{10}(R)} \exp \left( \frac{2(\ln 10)z + 2\sigma^2(\ln 10)^2}{b^2} \right) \]

\[ \times \int_0^\infty \exp \left( -\frac{k^2}{2\sigma^2} \right) dk, \]

(8)

where $B = z - b \log_{10}(R) + (2\sigma^2(\ln 10)/b$. Let $l = k/\sqrt{\sigma}$. Decomposing the integral into the standard form of the error function, then

\[ f_Z(z) = \frac{(\ln 10)}{b^2 \log_{10}(R)} \exp \left( \frac{2(\ln 10)z + 2\sigma^2(\ln 10)^2}{b^2} \right) \]

\[ \times \left[ \exp \left( -\frac{l^2}{2\sigma^2} \right) \sqrt{\frac{2\pi}{l}} \right], \]

(9)

where

\[ C = \frac{z}{\sqrt{\sigma}} + \frac{b \log_{10}(R)}{\sqrt{2\pi}} + \frac{\sqrt{2\pi}(\ln 10)}{b}. \]  

(10)

Using the definition of the error function as follows:

\[ \text{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt, \]  

(11)

we get

\[ f_Z(z) = \frac{(\ln 10)}{b^2 R} \exp \left( \frac{2(\ln 10)z + 2\sigma^2(\ln 10)^2}{b^2} \right) \]

\[ \times [1 - \text{erf}(C)], \]

(12)

Finally, we solve for the pdf of

\[ L = a + b \log_{10}(X) + N(0, \sigma^2). \]  

(13)

This final step translates to a shift and the pdf of $L$ is given as

\[ f_L(l) = \frac{(\ln 10)}{b^2 R} \exp \left( \frac{2(\ln 10)(l - a) + 2\sigma^2(\ln 10)^2}{b^2} \right) \]

\[ \times [1 - \text{erf}(D)]; \quad \forall l, \]  

(14)
where
\[ D = \frac{\ell b - ab - b \log_2 R + 2b^2 (\ln 10)}{2b^2}. \]

Equation (14) gives the pdf of path loss distribution in a circular scenario of radius \( R \) as seen from the centre of the circle, using an alternate expression for the error function as shown in [7], (14) can be written as
\[
 f_D(\ell) = \frac{(\ln 10) \exp\left\{ \frac{2\ell \log_2 R}{b^2} \right\}}{b^2} \times \left( 1 - \left( 1 - \frac{2}{\pi} \right) \exp\left\{ - \frac{2D}{2\sin^2 \theta} \right\} \right) \times \text{sign}(D),
\]
∀\( \ell \),

where \( D \) holds the same meaning as defined above and \( \text{sign}(\cdot) \) is the signum function.

3. Results

The parameters specified in the UMTS path loss model [8] are used for the simulations (intercept, \( a = 37 \) and \( b = 30 \)). The match between theory and simulations is investigated for varying circle radii and standard deviations for the log-normal shadowing component. Simulations are also carried out with the nodes distributed uniformly in hexagons having the same major radius as the circles to demonstrate the practicality of the derived theory.

The simulation is run by uniformly distributing 100,000 nodes in a circle or hexagon of the specified radius and then calculating the distance between the centre and each point. The histogram of these distances is then compared against theory. Figure 1(a) shows the match between the pdfs obtained through simulations and those derived in Section 2 for varying scenario radii and log-normal shadowing standard deviation values. Good agreement between theory and simulation is seen in all cases. Furthermore, it is observed that the theory for uniformly distributed nodes in a circle very closely approximates the case when the nodes are uniformly distributed in a hexagon having the same major radius as the circle. As expected, the pdf for the hexagonal case shifts to the left. This is because the major radius of the hexagon is the same as the radius of the circle, causing the hexagon to fit inside the circle. Therefore, there are fewer nodes not covered by nodes in the hexagonal case which causes the effect. The situation would be reversed if the minor radius of the hexagon were made equal to the radius of the circle. Figure 1(b) shows the cumulative distribution functions (cdfs) associated with the pdfs depicted in Figure 1(a).

4. Conclusion

This paper has presented an analytical derivation of the pdf of path loss distribution between the centre of a circle and uniformly distributed nodes within it.

The derived pdf assists in calculating the carrier-to-interference ratios, interference thresholds and exclusion regions in ad hoc and sensor networks. In addition, it is envisaged that the result can be used to develop and assess routing and scheduling algorithms for such networks without running time-consuming Monte Carlo simulations.
References


Star-NODE Identification in Self-Organising Wireless Networks

Zubin Bharucha, Sinan Sinanovic and Harald Haas
Institute for Digital Communications
Joint Research Institute for Signal and Image Processing
University of Edinburgh
Edinburgh, EH9 3JL, UK
Email: (z.bharucha, s.sinanovic, h.haas)@ed.ac.uk

Abstract—Self-configuring, hierarchical, ad hoc, wireless networks are fast becoming the focus of research for spectral efficiency and energy efficiency reasons. Such networks can be considered as graphs where a node represents a transceiving unit and an edge represents a communication link between two nodes. In order to probabilistically analyse connectivity issues in such graphs, the concept of the "star-node" is introduced here. A star-node is a node whose path loss to multiple nodes in its vicinity falls below a given threshold $\delta$; it is capable of sustaining “healthy” communication links to multiple neighbours. Star-nodes are important in the context of ad hoc and sensor networks since nodes in a self-organising network must be able to identify their neighbours, i.e., those nodes with which viable communication links can be established. The probability of finding such star-nodes is analytically derived for a uniform user distribution in a circular scenario. The theory is tested against Monte Carlo simulations and a very good match has been found.

I. INTRODUCTION

One of the most powerful methods of boosting wireless capacity is by shrinking the cell size. The reason for this is that smaller cell sizes enable the efficient spatial reuse of spectrum [1]. An added advantage is that the shorter transmission distances require less transmit power (green radio). However, reusing resources leads to an increase in interference. Therefore, future wireless network solutions are envisaged to be characterised by the lack of frequency planning [2], whereby fixed resources are opportunistically used. Dynamic, ad hoc, self-organising and spectrum-sharing networks using picocell/microcellular structures are considered as improvements to the current wireless network deployments which do not efficiently utilise the available bandwidth.

Making use of existing infrastructure and assigning a gateway mobile (GM) to each cluster of users [3] is one such proposal. This GM then communicates with the base station (BS), thereby doing away with the need for each individual mobile station (MS) to communicate with the BS.

In order to mathematically analyse such scenarios, the concept of the star-node is introduced. Consider a graph consisting of $n$ nodes/vertices. The degree of a node is defined as the number of edges incident to it. We define three types of nodes: a “star-node” is a node that has degree at least $k$ ($3 \leq k \leq n - 1$), a “chain-node”, on the other hand, is one whose degree is 2 and an “end-node” is a node with degree 1. Two nodes are assumed to be “connected” if the path loss between them falls below a pre-defined threshold. Such a link between two connected nodes is called a “healthy” link. Only star-nodes are considered in this paper. The probability of the existence of a specified number of star-nodes in a graph of $n$ nodes is derived in this work.

In [4], the authors show the relation between $k$-connectivity (a graph is $k$-connected if there is no set of $k - 1$ nodes whose removal will partition the graph) in a network of $n$ nodes and their transmission ranges. A transmission range, $\delta$, is defined such that two nodes within a distance $\delta$ of one another are said to be capable of sustaining communication with one another. The value for $\delta$ is calculated such that the network still remains $k$-connected with a certain probability ($\theta$). The network is capable of sustaining $k - 1$ link faults. In that work, the lower bound for the probability of a network consisting of $n$ nodes ($n > k > 0$) being $(k + 1)$-connected has been calculated. However, these results are valid only for $n > 500$.

In this work, two nodes are said to sustain communication between one another if the path loss between them falls below some pre-defined threshold. This is a more natural assumption than the distance-based approach used in [4] because the path loss also includes a random log-normal shadowing component which can cause two nodes that are close to one another to be out of communication range. Furthermore, the network size considered here is $n \geq 500$. Since the theory derived in [4] is not applicable for small networks, it cannot be used here.

The theory described in this paper lends itself very nicely to the analysis of ad hoc and sensor networks. It can be used to find the number of well-connected nodes in a randomly deployed sensor network over a given area. Conversely, it can also be used to find the ideal node density if the required number of well-connected nodes and network coverage area is known a priori.

The rest of the paper is organised as follows. Section II contains a brief introduction to random graph theory. The star-node detection theory is described in Section III. The derived theory is verified through Monte-Carlo simulations in Section IV. Finally, Section V contains the concluding remarks.

978-1-4244-2515-0/09/$25.00 ©2009 IEEE
II. RANDOM GRAPHS

In the following sections, random graph theory [5] will be used to derive results pertaining to star-node detection. The theory of random graphs lies at the intersection between graph theory and probability theory, and studies the properties of typical random graphs. A random graph is obtained by starting with a set of $n$ vertices and adding edges between them at random. Different random graph models produce different probability distributions on graphs. We deal specifically with the Erdős-Rényi model, commonly denoted as $G(n, p)$ in which each of the $\binom{n}{2}$ possible edges occurs independently with probability $p$. Random geometric graph theory [6] takes into account physical proximity of the nodes, i.e., the probability of an edge existing between two nodes, $p$, is dependent on the distance between them. However, due to the asymptotic nature of its results, it is outside the scope of this work.

Two functions $\Lambda(n)$ and $\theta(n)$ are said to be asymptotically equal to one another if $\lim_{n \to \infty} \frac{\Lambda(n)}{\theta(n)} = 1$. This asymptotic relation (as notation) is used extensively in the following section. If a graph with $40$ nodes is considered, the total number of labelled graphs possible with $40$ nodes is $\binom{40}{2} \approx 6.3591 \times 10^{21}$, which, for practical intents and purposes, approaches infinity.

III. Star-Node Detection

The path loss between two points is generally represented as some power of distance between them, denoted by $10^{-a}$, where $a$ is the path loss exponent, plus a random variation about this power law due to shadowing, $\xi$, which is a zero-mean, normally distributed random variable with standard deviation $\sigma$, i.e., $N(0, \sigma^2)$, as shown in [7]. Therefore, the path loss, $L$, in dB, between two points is written as

$$L = a + 10 \log_{10}(X) + \xi,$$

where $a$ is an intercept which is the free-space path loss at some close-in distance $a$, and $X$ is the distance between the points, $a$, divided by $d_0$, i.e., $X = d/d_0$.

If $L$ is a random variable associated with the random variable $L$, the pdf (probability density function) of path loss distribution for uniformly distributed nodes in a circle of radius $R$ as seen from the centre is found to be [8]

$$f_L(l) = \frac{\ln(10)}{b^2} C \left[1 - \text{erf} \left( \frac{D}{b} \right) \right], \quad \forall l,$$

where

$$C = \frac{2(\ln(10))(\epsilon - a)}{b}, \quad \frac{2\sqrt{\ln(10)}}{b}^2 \quad \text{and} \quad D = \frac{\epsilon b - \sqrt{\ln(10)}}{b} R.$$

For the rest of the paper, $p$ (edge probability) is used to denote the probability with which two nodes are connected to one another via a healthy link. The cdf (cumulative distribution function) associated with the pdf shown in (2) shows the relationship between $p$ and a path loss value. Thus, the value of $p$ is directly related to the path loss threshold, i.e., the probability that two nodes are connected to one another via a healthy link increases if the path loss threshold is increased and vice-versa. Furthermore, "K-star-node" is used to denote a node that is of degree exactly $k$, i.e., a star-node having healthy links to exactly $k$ other nodes. Similarly, "K-star-nodes" is used to denote a node of degree at least $k$, i.e., a star-node having healthy links to at least $k$ other nodes. Finally, $X_k$ is used to denote the number of $k$-star-nodes in a given graph and $\mathbb{E}[X_k]$ denotes the number of $k$-star-nodes in a given graph and

A. Probability of detecting at least one star-node

It has been shown in [5] that the probability of finding exactly $r$ $k$-star-nodes, i.e., $P(X_k = r)$ is

$$P(X_k = r) \sim e^{-n_0 k_r / r!},$$

where $k_r = n_0 k_r (n_0 - 1), p = n_0 (n_0 - 1) / n(n_0 - 1) - 1$ and $q = 1 - p$ and $n$ is the number of nodes in the graph.

Let $k_r = n_0 (n_0 - 1), p = n_0 \sum_{j=0}^{n_0} (j; n_0 - 1) \frac{n_0 j}{n_0 - 1}$ and $q = 1 - p$. The asymptotic of (3) holds if $X_k$ is replaced by $Y_k$ and $k_r$ by $k_r$. Thus the probability of finding exactly $r$ $K$-star-nodes, i.e., $P(Y_k = r)$ changes to

$$P(Y_k = r) \sim e^{-n_0 k_r / r!}.$$

The probability of detecting at least one $K$-star-node is of interest here. The probability of detecting no $K$-star-nodes is used to arrive at the required probability. Therefore,

$$P(Y_k = 0) \sim e^{-n_0 k_r} \sim \left( \frac{\epsilon b}{2b} \right)^n \left( 1 - \frac{\epsilon b}{2b} \right)^n,$$

Eq. (6) can be used to find the probability of detecting at least one $K$-star-node as

$$P(Y_k \geq 1) = 1 - P(Y_k = 0) \sim \left( 1 - \left( \frac{\epsilon b}{2b} \right)^n \right).$$

Eq. (8) describes the asymptotic probability that a graph consisting of $n$ nodes distributed uniformly within a circle of a certain radius contains at least one star-node for a given edge probability $p$, i.e., it holds as $n \to \infty$. A non-asymptotic probability for the detection of at least one star-node is now derived.

Consider a fully connected graph consisting of $n$ nodes which are uniformly distributed in a circular area. Let $N = \binom{n}{2}$ denote the maximum number of possible edges in this graph. For a particular edge probability $p$, the expected value of the number of edges in the graph is $Np$. Using this, the expected value of the number of edges per node is

$$E(n_e) = \frac{2}{n} Np \quad \text{and} \quad n_e = (n - 1)p.$$

A factor of 2 is introduced in (9) because every edge joins two nodes.
For a node to qualify as a $K$-star-node, it must have at least $k$ edges originating from it. Putting this in (10) and rearranging gives $p = \frac{N-k}{N}$. If this condition is met, then every node has, on average, $k$ edges originating from it. Thus the average number of edges in the graph is $Np = \frac{kN}{2}$. Therefore, if it is ensured that the graph contains at least $\frac{kN}{2}$ edges, then it contains at least one $K$-star-node. The rationale behind this statement is as follows: if the mean of an ensemble of values is $m$, then there must be at least one value $\geq m$. Using this argument, the guarantee of detecting at least one star-node for a graph consisting of $n$ nodes with an edge probability of $p$ is given by the binomial distribution function as

$$P_{\text{match}}(Y_k \geq 1) = \sum_{j=[\frac{kN}{2}]}^{N} \left( \begin{array}{c} N \\ j \end{array} \right) p^j (1-p)^{N-j}$$  

(11)

$$= 1 - \sum_{j=0}^{[\frac{kN}{2}-1]} \left( \begin{array}{c} N \\ j \end{array} \right) p^j (1-p)^{N-j}$$  

(12)

where $[\cdot]$ denotes the ceiling function. Fig. 1 makes this clearer through an example. The binomial probability is calculated and plotted in for a graph with $n = 5$ and $p = 0.5$. A five node graph consisting of 5 edges is shown on the left. It is seen here that for certain edge configurations, the graph may contain one or more star-nodes but there will also be cases when there are no star-nodes (as shown in this case). The same graph consisting of $\left[\frac{5N}{2}\right] = 8$ edges is shown on the right. Here, it is seen that regardless of the configuration of the edges, the graph will always contain at least one star-node. Eq. (12) calculates the probability of the graph having $\left[\frac{5N}{2}\right]$ or more edges for a certain value of $p$. Such graphs will contain at least one $K$-star-node.

This clearly overshoots the probability described in (8) because those graphs containing star-nodes in which the number of edges is $< \left[\frac{kN}{2}\right]$ are disregarded. This causes the probability of detection of at least one $K$-star-node using (12) to be lower than that calculated using (8) for any $p$. However, unlike (8), this simple probability is not asymptotic in nature and holds for even very small values of $n$.

For $p \ll 1$ and $n \gg 1$, the binomial probability in (12) can be approximated with the Poisson law as $b(k, n, p) \approx \frac{ke^{-k}}{k^k}$ [9], where $k = np$. Thus, (12) becomes

$$P_{\text{match}}(Y_k \geq 1) = 1 - \sum_{j=[\frac{kN}{2}]}^{N} p^j e^{-p}$$  

(13)

where $\vartheta = np$. The cdf of the Poisson distribution can be expressed as

$$\sum_{k=0}^{[\frac{kN}{2}]} \frac{x^k e^{-x}}{k!} = \frac{\Gamma(\vartheta, \vartheta)}{\Gamma(\vartheta)}$$

where $\Gamma(\alpha, \vartheta) = \int_\vartheta^\infty t^{\alpha-1} e^{-t} dt$ is the upper incomplete Gamma function. Thus (13) becomes

$$P_{\text{match}}(Y_k \geq 1) = 1 - \frac{\Gamma(\left[\frac{kN}{2}\right] + \vartheta)}{\Gamma(\left[\frac{kN}{2}\right] + \vartheta + 1)}$$  

(14)

This is an equivalent representation of (12). It can be used for large values of $n$ since it does not deal with $N$, which increases quadratically with $n$.

**B. Probability of detecting exactly one star-node**

The aim now is to find the probability that a graph contains exactly one $K$-star-node. Therefore, a graph containing any nodes of degree higher than $k$ does not fall under this category. Using (3), this probability can be found as

$$P(Y_k = 1) = 1 \land X_{\leq k} = 0 = e^{-\lambda_k} \lambda_k \prod_{i=k+1}^{n} e^{-\lambda_i}$$  

(15)

Practically, from the point of view of sensor networks, the most useful probability is that of detecting exactly one star-node from $n$ uniformly distributed nodes in a circular scenario ($P(Y_k = 1)$) since the existence of a star-node is a prerequisite for being able to establish a hierarchical network where the star-node acts as cluster head. Arriving at this probability is straightforward as presented in [5] as

$$P(Y_k = 1) = e^{-\lambda_k} \lambda_k$$  

(16)

**IV. RESULTS**

A network of uniformly distributed nodes in a circular area with radius 100 m is assumed. The path loss parameters are set to $a = 5\sigma, b = 30$ and $\sigma = 6$ dB. The cdf associated with (2) is used to map the relationship between edge probability $p$ and the path loss threshold. This is then to calculate the theoretical probabilities described in (3) through (16). These are compared against simulations in order to test their accuracy. The results in this section show that in spite of the asymptotic nature of the theory derived, there is a strong match between simulations and theory. In each case, the probability of star-node detection is shown for varying values of path loss thresholds as well as the corresponding edge probabilities, $p$.  

145
The probability of detecting at least one $K$-star-node as described by (8) is shown in Fig. 2. Here, the probabilities of detecting at least one $K$-star-node from 40 and 60 uniformly distributed nodes are shown. It is seen that the probability of star-node detection increases as the path loss threshold is increased. This is obvious since an increase in the path loss threshold translates to an increase in the edge probability (shown on the upper $x$-axis). It is also seen that as the density of nodes is decreased, the curve shifts to the right. As the density of nodes is reduced, the average distance between nodes increases. Therefore, for the same path loss threshold, the probability of star-node detection is reduced for lower node densities. For the scenario shown in the figure, node density is $\sim 1273$ nodes per sq. km. for the 40 node case and $\sim 1910$ nodes per sq. km. in the 60 node case. Finally, it is interesting to note the range of $p$ values on the upper $x$-axis of this figure. For the 60 node case, to achieve 90% probability of star-node detection, the required edge probability is $\sim 0.63$ and it reduces to $\sim 0.2$ for 10% probability of detection. This shows that the probability of the existence of a star-node is very sensitive to the edge probability, $p$.

Fig. 3 shows the probability of detection of at least one $K$-star-node using the approach described by (14) from a network consisting of 40 and 60 uniformly distributed nodes. The curves in Figs. 2 and 3 are very similar in shape, however, it is clear that the curves depicted in Fig. 3 are offset to the right. For the same probability of star-node detection, using the approach described by (14) requires the path loss threshold to be set higher than the approach described by (8). This is because in this case, the probability of star-node detection requires that the average number of edges in the network is at least $\binom{\frac{n}{2}}{2}$ which disregards a whole class of graphs in which a star-node exists (namely those cases when the total number of edges in the graph is $< \binom{\frac{n}{2}}{2}$). Thus, in order to enforce the new star-node detection condition, the path loss threshold must be higher than in the previous case. The set of curves shown in this figure are very sensitive to changes in the path loss threshold. For example, in the 60 node case, to increase the guarantee of detection from 10% to 90% requires an increase in the threshold of only 2 dB (from 74 dB to 76 dB). This shows that the system is very sensitive to even a small change in threshold values. This confirms the 0-1 law (discovered by Erdos and Kored [5]) which states that many important properties (such as graph connectedness, in this case) of random graphs appear quite suddenly.

Fig. 4 shows the probability for the detection of exactly one $K$-star-node and $K$-star-node as described by (15) and (16) respectively. The shape of the curves is explained by the fact that at extremely low path loss thresholds, it is very unlikely that a node has several edges originating from it. However, as the threshold is increased, a critical level is reached at which point the likelihood of the graph containing exactly one node of the desired degree is the highest. Beyond this point, as the path loss criteria gets more relaxed, nodes of degrees higher than $k$ begin to emerge which then reduces the probability of the graph containing exactly one $K$-star-node or $K$-star-node with all other nodes of degree $< k$. Furthermore, the probability of detecting exactly one $K$-star-node is higher than the probability of detecting exactly one $K$-star-node for any path loss value because $K$-star-node detection is $K$-star-node detection in addition to the detection of star-nodes with degrees higher than $k$. Therefore, $K$-star-node detection can be considered as a subset of $K$-star-node detection.

Finally, the probability of detecting exactly 10 $K$-star-nodes from among 100 randomly distributed nodes is shown in Fig. 5. In order to visualise a similar situation, Fig. 6 shows one instance of a 100 node network with exactly four detected $K$-star-nodes. The path loss threshold is set to 65 dB in this case. In order to avoid cluttering, only the first three healthy
Selected Publications

Fig. 4. The probability of detecting exactly one $k$-star-node and $K$-star-node (with $K = 6$) from 100 uniformly distributed nodes in a circular scenario of radius 100 m.

Fig. 5. The probability of detecting exactly 10 $K$-star-nodes ($k = 5$) from 100 uniformly distributed nodes in a circular scenario of radius 100 m.

links are shown for every detected star-node. The links are labelled with their path loss values (in dB). It can be seen that some nodes that are separated by large distances have smaller path losses than shorter links which is a direct consequence of log-normal shadowing.

V. CONCLUSION

The theory governing the existence and detection of so-called star-nodes has been derived in this paper. The pertinence of star-node detection theory is apparent in the context of ad hoc and self-configuring sensor networks because the existence of star-nodes is instrumental in the establishment of a network hierarchy in decentralised and self-organising networks. This randomly developed "structure" can be exploited for intelligent and energy efficient routing, intelligent network control as well as radio resource allocation. This work also helps answer an important question in terms of ad hoc and sensor networks: what node density can a cluster of transceiving nodes sustain communication in an ad hoc fashion? Finally, the implications of the 0-1 law have revealed very good design information about the minimum node density and link budget requirements (transmit power and receiver sensitivity) for ad hoc networks.

ACKNOWLEDGEMENT

Hamil Haas acknowledges the Scottish Funding Council support of his position within the Edinburgh Research Partnership in Engineering and Mathematics between the University of Edinburgh and Heriot-Watt University.

REFERENCES


THROUGHPUT ENHANCEMENT THROUGH FEMTO-CELL DEPLOYMENT

Zubin Bharucha and Harald Haas
Institute for Digital Communications, School of Engineering and Electronics
The University of Edinburgh, Edinburgh EH9 3JL, UK
{z.bharucha, h.haas}@ed.ac.uk

Ivan Ćosović and Gunther Auer
DOCOMO Euro-Labs
Landsberger Strasse 312, 80687 Munich, Germany
auer@docomolab-euro.com

Abstract. This paper studies the impact of femto-cell underlay deployment that share radio frequency resources with urban macro-cells. Due to the random and uncoordinated deployment, femto-cells potentially cause destructive interference to macro-cells and vice versa. On the other hand, femto-cells promise to substantially enhance the spectral efficiency due to an increased reuse of radio resources. The performance of systems with femto base station (FBS) deployment is compared to a system where all users, including indoor users, are served by the macro base station (MBS). In addition, the impact of closed-access and open-access femto-cell operation is examined. It is demonstrated that significant throughput gains can be achieved through such FBS deployment, regardless of whether closed-access or open-access is considered. Results clearly indicate that the benefits of FBS deployment by far outweigh their impact on the macro-cell capacity.

1. Introduction

There is a growing demand for increased user and system throughput in wireless systems. Naturally, such rapidly increasing demand is served by higher bandwidth allocation, but since bandwidth is scarce and expensive, a key to substantial throughput enhancement is to improve the reuse of radio frequency resources. One of the most powerful methods of boosting wireless capacity is by shrinking the cell size. The reason for this is that smaller cell sizes enable the efficient spatial reuse of spec-
trum [1]. Furthermore, the shorter transmission distances allow for the use of higher order modulation schemes. While decreasing the cell size boosts system capacity, the cost involved is becoming increasingly prohibitive, due to the required installation of new network infrastructure.

Studies indicate that a significant proportion of data traffic originates indoors [2]. Poor signal reception caused by penetration losses through walls severely hampers the operation of indoor data services. Therefore, the concept of 3rd generation (3G) femto-cells has recently attracted considerable interest. FBSs are low-cost, low-power, short-range, plug-and-play base stations, which aim to extend and improve macro-cell coverage in indoor areas. FBSs are directly connected to the backbone network and user equipment (UE) located indoors communicates directly with FBSs. FBSs therefore offload indoor users from the macro-cell, thus potentially enhancing the capacity both, indoors as well as outdoors.

In [3, 4], the authors propose the TDD underlay concept. Owing to the asymmetric nature of traffic, one of the frequency division duplex (FDD) bands (the underloaded one) can be split in time such that the FBS transmits and receives information from its associated femto user equipment (FUE) in a time division duplex (TDD) fashion. In this work, both macro and femto cells operate in the same radio frequency spectrum in frequency division duplex (FDD) mode, compliant with the specifications for beyond 3G mobile communication systems [5]. Like in the original TDD underlay concept [3], the FBS backhauls data through a dedicated broadband gateway (DSL/cable/Ethernet/etc.) to the cellular operator network. There are several obvious advantages from femto-cell deployment, the most important of which is that the operator is able to concentrate on providing better service to the outdoor macro-cell UEs (MUEs). Another selling point for operators is that high throughput coverage is extended to the indoor environment.

However, it must be kept in mind that FBSs are deployed without network planning. Since FBSs operate on the same bands as MBSs, their deployment introduces additional interference. Furthermore, questions regarding security are raised with the deployment of FBSs, such as “should the FBS allow any UE in its vicinity to connect to it?” or “should the FBS maintain a list of UEs that are exclusively allowed to use its resources?” and “who should control access to the FBS?”.

The discussion is therefore taken in the direction of open-access versus closed-access systems. Open-access allows any UE to connect to the FBS whereas closed-access only allows a specified set of UEs to connect to the FBS. Closed-access systems are therefore susceptible to higher interference from indoor UEs that lie geographically in a femto-cell but are not connected to its FBS.
Recent studies on femto-cells shows the geographic distribution of throughput for a deployment of open-access femto-cells in a cellular network [6] and the impact of FBS deployment on macro-cell performance [7]. In this work, system-level simulations are carried out for three different scenarios. In all systems, indoor and outdoor users exist and are randomly distributed. A system without FBS deployment, where all users (indoors or outdoors) are exclusively served by macro-cells serves as benchmark system. Systems with FBS deployment are distinguished between open and closed access (see Figure 1). We demonstrate through system level simulations that FBS deployment, no matter what the access method is, has a clear advantage over the benchmark system in terms of user and overall system throughput.

The remainder of this paper is organised as follows. Section 2 describes the system model and simulator setup. Simulation results are presented in Section 3 and Section 4 highlights the key findings.

2. System Model and Simulation Setup

2.1 User Distribution

The simulation area comprises a two-tier, tessellated hexagonal cell distribution. In order to eliminate edge effects, an additional two tiers are simulated, however statistics are taken only from the first two tiers. Femto-cells have a circular area, each with a fixed radius and they are uniformly distributed over the four-tier structure with a given density. A random number of users and one FBS are uniformly distributed in each femto-cell. In the macro-cell, the MUEs are uniformly distributed over the entire region. This ensures that there is a certain probability (dependent on femto-cell and MUE density) that MUEs lie within femto-cells. In the case of open-access systems, such MUEs are assimilated into the femto-cell and are served by the associated FBS. In the case of closed-access systems, these MUEs are still served by the MBS.
the benchmark system, all UEs are MUEs (and are located indoors or outdoors).

2.2 Path Loss Models

Three path loss models (along with their respective delay profiles) are used - the urban micro (UMi) model for the macro-cell channel, the indoor hotspot (InH) model [8] for the femto-cell and the indoor-to-outdoor model to simulate the channel between entities lying indoors and outdoors. For each link in the system, the probability of line of sight (LoS) is calculated as specified in the appropriate path loss model and based on the LoS condition, the associated path loss model is applied to that link. Furthermore, a wall penetration loss of 20 dB is used to model outdoor-to-indoor links (and vice-versa). The delay profiles associated with these path loss models used to generate frequency-selective fading are provided in [8].

2.3 Interference and SINR Calculation

Once the users are distributed, log-normal shadowing maps containing correlated shadowing values in space are generated. Using these and the path loss models, MUEs are associated with the MBS to which they have the least path loss. Depending on whether open or closed access is considered, MUEs that lie within femto-cells are either assimilated or not.

A resource block (RB) represents one basic time-frequency unit. The RBs are distributed equally among the MUEs of a macro-cell and the same resources are reused within each femto-cell. In order to allow for a fair comparison, the transmit power per RB is computed a priori and is kept constant for all systems.

The signal-to-interference-plus-noise ratio (SINR) for user \(i\) on RB \(j\) (\(\gamma_i^j\)) is calculated as

\[
\gamma_i^j = \frac{P_i^j}{(I_i^j + N)},
\]

where \(P_i^j\) is the useful received power for user \(i\) on RB \(j\), \(I_i^j\) is the interference seen by that user on that RB and \(N\) is the thermal noise in the system. There are 8 interference scenarios: \(\text{MBS} \leftrightarrow \text{MUE}, \text{FBS} \leftrightarrow \text{FUE}, \text{MBS} \leftrightarrow \text{FUE}, \text{FBS} \leftrightarrow \text{MUE}\), where “\(\leftrightarrow\)” represents bi-directional interference. The first four represent “inter-site” interference scenarios, i.e., the interference originates from neighboring cells (macro or femto). The last four interference scenarios can be caused within the same cell. Since all the resources are reused within the femto-cell, FUEs are affected by the MBS of the macro-cell within which they lie (and vice-versa) and FBSs are interfered with by the MUEs which lie in the same macro-cell. The
last two interference scenarios are potentially the most detrimental in closed-access systems. This is because for closed-access, an MUE may lie within a femto-cell while still being connected to the MBS, thereby causing severe MUE→FBS interference in the uplink (UL). Only the first two interference scenarios exist for the benchmark system, since all users are served by macro-cells.

3. Results

Simulations are run for a full-buffer traffic model, i.e., all users in the system are active simultaneously. Furthermore, a quasi-static channel model is assumed, where channel variations due to mobile velocities of mobile users are neglected. Perfect synchronisation in time and frequency is assumed, so that interference between neighboring RBs is avoided. Based on the achieved SINR per RB, the aggregate throughput for user $j$ is calculated as

$$T^j = \sum_{i \in \mathcal{R}^j} W_{RB} \log_2 \left( 1 + \gamma_i^j \right),$$

where $\mathcal{R}^j$ is the set of RBs allocated to user $j$, $W_{RB}$ is the bandwidth of one RB and $\gamma_i^j$ is the achieved SINR on the $i^{th}$ RB of user $j$. The sum system throughput is generated as the sum of the individual user throughputs. The number of FUEs per femto cell is uniformly distributed with the minimum being one and the maximum being four. The rest of the parameters used in the simulation are taken from [5, 9–11] and are shown in Table 1.
The overall sum system throughput for both uplink (UL) and downlink (DL) is depicted in Figure 2. For systems with FBS deployment the aggregate femto and macro user throughputs is compared to the benchmark system where all users are served by the macro-cell. These results highlight the achieved gains through FBS deployment. It is seen that the UL system throughput for systems with FBS deployment are approximately two orders of magnitude higher than for the benchmark system. While the corresponding DL gains through FBS deployment are still impressive, the increase in DL system throughput is significantly lower compared to the UL. The reason for this is twofold: firstly, in the DL the MBS transmit power per RB is higher than in the UL, which results in an increased DL macro-cell throughput, which in turn cause more DL interference to femto-cells. Hence the DL throughput of femto-cells is lower compared to the UL. Secondly, in the UL, even if there is an MUE very close to a femto-cell, it typically does not transmit on all RBs. Thus, fewer RBs are affected.

In Figure 2 we also observe that the system throughput for closed and open-access systems are nearly identical in DL and UL despite the fact that MUEs lying indoors suffer in terms of throughput. This is because in these simulations, the number of MUEs lying indoors is small in comparison to the total number of UEs in the cell and therefore this does not significantly affect the system throughput of closed-access. For the parameters used in this simulation, the probability of an MUE lying indoors is less than 5%, which is reflected in the results.

Figure 3(a) shows the throughput for only femto users in the UL for varying FUE transmit powers. It can clearly be seen that as the FUE transmit power is increased, the user throughput is boosted. The
Throughput Enhancement through Femto-Cell Deployment

Figure 3. Femto user throughput for open and closed-access systems. The CDF of the user throughput for FUEs is plotted for UL (a) and for DL (b).

close-up also shows that closed-access outperforms open-access by a slim margin. This is because more FUEs are served by the FBS for open-access than for closed-access, as a result of the fact that some users lying inside femto-cells for closed-access are served by the MBS. Due to this, for open-access, each user, on average, is allocated fewer RBS, thus marginally bringing down the user-throughput for open-access, despite the increased interference caused by MUEs lying inside femto-cells for closed-access. The two different slopes in the CDF arise from the fact that there can be FUEs having LoS and non LoS conditions with the associated FBS.

The throughput for only femto users in the DL for varying FBS transmit powers is shown in Figure 3(b). Here, the trends are the same as in the previous case. However, it must be noted that the user throughput is reduced in comparison to those seen in Figure 3(a). The reason is that the DL interference is, on average, higher than in the UL, due to the higher available transmit power at the MBS.

Figure 4(a) shows the cumulative distribution function (CDF) of macro-user throughput in the UL for varying FUE transmit powers. For the benchmark system, all users are included in the statistics because they are all served by the MBS. Interestingly, FBS deployment achieves an approximately 5-fold gain at the 90th percentile compared to the benchmark system. In case of FBS deployment, the FBS offloads the MBS from serving femto-cell users, thus freeing resources that can be given to macro users. Looking closer (inset), it is seen that open-access outperforms closed-access. This is expected because for open-access, there are no MUEs lying inside femto-cells, avoiding destructive interference.
On the other hand, the signal reaching the MBS from indoor MUEs for closed-access is highly attenuated (due to wall penetration losses, etc.), thus significantly bringing down the UL throughput for such users. Finally, it is seen that varying the FUE transmit powers does not significantly affect the macro-cell performance for systems with femto-cell deployment.

The same trends continue in Figure 4(b) which depicts the CDF of user throughput served by the macro-cell in the DL for varying FUE and FBS transmit powers. As in the previous case, for the benchmark system the statistics of all users in the system are gathered, while only macro users are measured for systems with femto-cell deployment. Here, all systems exhibit slightly higher user throughput owing to the higher transmit power per RB in the DL. Hence, in Figure 4(b) the difference between open and closed-access is slightly higher than in Figure 4(a) (see inset).

In order to assess the difference in performance between open and closed-access systems, those MUEs lying indoors (for closed-access) are identified and their throughput performance is compared against open-access. Figures 5(a) and 5(b) show the throughputs of such MUEs in UL and DL (notice the difference in scale of the x-axes). As expected for all FBS/FUE transmit powers, open-access significantly outperform closed-access, as for open-access, UEs are assimilated by the FBS. Therefore, for closed-access systems, wall penetration losses and longer transmit distances drastically reduce throughput. Furthermore, for open-access the UL performance is superior to the DL. This is attributed to the fact that interference is lower in UL than in DL. The reverse holds true for
closed-access systems. Only for low FBS transmit powers of $-30$ dBm, a median throughput of $\approx 200$ kbps is achieved. At the other powers, the interference from the femto-cell is too high to support reasonable throughputs.

4. Conclusion

Femto-cell deployment poses a viable complement to cellular networks. Operators need to bear low cost in their deployment, since they are installed directly by the users themselves. Furthermore, since they share both the radio access scheme and the frequency band with MBSs, they are compatible with legacy UEs. Aside from these benefits, a cellular network stands to significantly gain in overall system throughput through the widespread deployment of FBSs. Not only do FBSs improve indoor coverage, bringing broadband-like experience directly to the handset, but they also offload resources from the MBS which can be utilised to improve coverage to outdoor users.

In terms of overall throughput, the difference between closed-access and open-access systems is almost negligible, because of the relatively low probability that a MUE is inside a femto-cell. However, even if a MUE is within a femto-cell, it might be able to receive from its MBS if the FBS transmit power is sufficiently low — which indeed is possible given the short distances in femto-cells. This means power control and intelligent resource scheduling in femto-cells are envisaged to further reduce the interference that femto-cell entities cause to macro-cell entities.
Acknowledgement

Initial parts of this work were supported by DFG grant HA 3570/2-1 as part of program SPP-1163 (adaptability in heterogeneous communication networks with wireless access – AKOM) while some latter parts of this work have been performed within the framework of the CELTIC project CP5-026 WINNER+.

References


Selected Publications

Femto-Cell Resource Partitioning

Zubin Bharucha*, Harald Haas*, Gunther Auer† and Ivan Covic‡

* Institute for Digital Communications
Joint Research Institute for Signal and Image Processing
School of Engineering and Electronics
The University of Edinburgh
EH9 3JL, Edinburgh, UK
{z.bharucha, h.haas}@ed.ac.uk

† DOCOMO Euro-Labs
80687 Munich, Germany
auer@docomolabs.com

Abstract—This paper studies the impact of a femto-cell underlay deployment that shares radio frequency resources with urban macro-cells. Femto-cells promise substantial gains in spectral efficiency due to an enhanced reuse of radio resources. However, owing to their random and uncoordinated deployment, they potentially cause destructive interference to macro-cells and vice-versa. In order to maintain reliable service of macro-cells, it is most important to mitigate destructive femto-to-macro-cell interference. In the downlink, this can be achieved by dynamic resource partitioning, in the way that femto base stations (BSs) are denied access to resources that are assigned to nearby macro mobile stations (MSSs). By doing so, interference to the macro-cells is effectively controlled, at the expense of a modest degradation in femto-cell capacity. The necessary signalling is conveyed through the wired backbone, using the downlink high interference indicator (DL-HII).

I. INTRODUCTION

There is a growing demand for increased user and system throughput in wireless systems. Naturally, such rapidly increasing demand is served by higher bandwidth allocation, but since bandwidth is scarce and expensive, a key to substantial throughput enhancement is to improve the reuse of radio frequency resources. One of the most powerful methods of boosting wireless capacity is by shrinking the cell size. The reason for this is that smaller cell sizes enable the efficient spatial reuse of spectrum [1]. Furthermore, shorter transmission distances allow for higher order modulation schemes, and a significant proportion of data traffic originates indoors [2]. Poor signal reception caused by penetration losses through walls severely hampers the operation of indoor data services. Therefore, the concept of 3rd generation (3G) femto-cells has recently attracted considerable interest [3,4]. Femto BSs are low-cost, low-power, short-range, plug-and-play BSs, which aim to extend and improve macro-cell coverage in indoor areas. Femto BSs are directly connected to the backbone network and MSSs located indoors communicate directly with femto BSs. Femto BSs therefore offload indoor users from the macro-cell, thus potentially enhancing the capacity both, indoors as well as outdoors.

In [5,6], the authors propose the time division duplex (TDD) underlay concept. Owing to the symmetric nature of traffic, one of the frequency division duplex (FDD) bands (the underloaded one) can be split in time such that the femto BS transmits and receives information from its associated femto MS in a TDD fashion.

In this work, both macro and femto-cells operate in the same radio frequency spectrum in FDD mode, compliant with the specifications for beyond 3G (B3G) mobile communication systems [7]. Deployments where femto-cells operate on separate bands from the macro-cell as considered in [8] are beyond the scope of this work since this research focuses on the impact of co-channel femto-cells on the macro layer and the mitigation of downlink interference caused by them. Like in the original TDD underlay concept [5], the femto BS backhauls data through a dedicated broadband gateway (DSL/cable/ethernet/etc.) to the cellular operator network. There are several obvious advantages from femto-cell deployment, the most important of which is that radio resources can be shifted to outdoor users, yielding better user performance (satisfied user criterion) and coverage. Moreover, femto-cell deployment could potentially lead to an overall reduced energy consumption as penetration losses due to walls are circumvented and sleep mode operation is more straightforward to implement in femto BSs. Another selling point for operators is that high throughput coverage is extended to the indoor environment, where it is most needed [2].

Femto BSs are deployed without network planning, so that their deployment introduces additional interference. Regarding hand-over between macro and femto-cells, two access control mechanisms, open-access and closed-access, are identified. In open-access femto-cells, macro MSSs get “assimilated” into the femto-cell, in the way that MSSs that lie within the coverage area of a femto-cell are handed over to the corresponding femto BS. In closed-access systems the femto BS only grants access to a particular set of authorized MSSs. It is these closed-access systems that cause (and receive) the most detrimental interference. This is because a “foreign” macro MS lying in the coverage area of a femto-cell is not allowed to communicate with the femto BS, but must communicate with the macro BS that lies outdoors. Due to wall penetration losses, such macro MSs receive a highly attenuated signal from the macro BS and, in addition, receive excessive interference originating from the femto BS whose coverage area the MS lies in.

The issue of downlink femto-to-macro interference in closed access is addressed in this paper. The main contribution is a dynamic, interference-avoidance, resource partitioning
approach which prioritises macro MSs. This means that femto-cells partition resources only if they cause high interference to nearby macro MSs. If no macro MS is affected, the femto-cell uses all resources (full frequency reuse). Existing interfaces and protocols for the signalling between macro and femto-cell entities are exploited. This is facilitated through the high interference indicator (HII) messages conveyed through the X2 interface via the wired backbone. For the 3GPP mobile communication system 3rd generation partnership project (3GPP) Long Term Evolution (LTE) [7], HII messages are specified to deal with macro-to-femto interference [9, 10] in the uplink. In this work, it is demonstrated that the framework of HII signalling can be readily applied to mitigate femto-to-macro interference in the downlink. In order to assess the impact of resource partitioning on macro and femto-cell performance system level simulations are carried out. In the macro-cell, two different reuse schemes are used in order to vary the interference originating from other macro-cells and thereby examine its impact on the overall system performance.

The remainder of this paper is organised as follows. Section II describes the state-of-the-art LTE inter-cell information exchange and how it can be used to carry out smart scheduling in the femto-cell. The system model and simulation setup are described in Section III, and results are presented in Section IV. Concluding remarks are given in Section V.

II. FEMTO-CELL RESOURCE PARTITIONING

A. System Model

The downlink of an orthogonal frequency division multiple access (OFDMA) system is considered, where the system bandwidth B is divided into N resource blocks (RBs), B = N·B0. An RB represents one basic frequency unit with bandwidth B0. The macro and femto BS transmit powers per RB are denoted by Pm and Pf respectively. Transmit powers across the RBs are maintained constant. Perfect synchronisation in time and frequency is assumed.

Universal frequency reuse is considered, so that both macro and femto-cells utilise the entire system bandwidth B. The set of available RBs N, with cardinality |N| = N, is distributed by macro and femto BSs among their associated macro and femto MSs respectively. The received signal power observed by MSu (where u is the user index) at RB n is given by

\[ Y_u^n = G_{mn}^u P_m + I_n^u + \eta_u \]  

(1)

where G_m^n is the channel gain between MS_u and its serving BS, and \( \eta_u \) accounts for thermal noise per RB. The transmit power is set to \( P_m = P_{m0} \) and \( P_f = P_{f0} \) if MS_u is served by a macro BS and a femto BS respectively. The aggregate interference \( I_n^u \) is composed of macro and femto-cell interference

\[ I_n^u = \sum_{n \in N_{m0}} G_{mn}^u P_m + \sum_{j \in N_{f0}} G_{jn}^u P_j \]  

(2)

where \( G_{mn}^u \) accounts for the channel gain between interferer i or j observed by MS_u. The sets of interfering macro and femto BSs are denoted by \( N_{m0} \) and \( N_{f0} \), respectively. If the MS in question is served by a macro BS, all femto BSs in the system are interferers, and in addition, all macro BSs other than the serving macro BS are also interferers. Similarly, if the MS in question is served by a femto BS, all macro BSs in the system are interferers, and in addition, all femto BSs other than the serving femto BS are also interferers. The signal-to-interference-plus-noise ratio (SINR) observed at MS_u amounts to

\[ \gamma_u^n = \frac{G_{mn}^u P_m}{I_n^u + \eta_u} \]  

(3)

Finally, the capacity \( C_u \) of user u is calculated using the Shannon capacity formula as

\[ C_u = \sum_{n \in N_u} \log_2 (1 + \gamma_u^n) \]  

(4)

where \( N_u \) is the set of RBs allocated to user u.

B. Downlink Interference Scenario for Clouded-access

As typically the macro BS transmit power exceeds the femto BS transmit power by several orders of magnitude, \( P_m \gg P_{f0} \), in most cases the interference seen by macro MSs will be dominated by macro BS interference. Only if a macro receiver MS_u is located in close proximity to a femto BS, MS_f, exposed to high femto BS interference \( G_{mf}^u P_f \) \( \in F_{mf} \).

In case MS_u is located indoors, the situation is exacerbated by the poor channel gains, \( G_{mf}^u \), to the serving macro BS, caused by high wall penetration losses. This MS_u is likely to experience poor SINR (3). With full frequency reuse, femto-cells utilise all N RBs. Therefore, the received SINR is likely to be unacceptable over the set of RBs allocated to MS_u.

C. Avoiding Femto-to-Macro Interference

Suppose that MS_u is located indoors within coverage of femto BSs, but served by a macro BS. An effective means of mitigating the destructive femto BS interference observed by MS_u is to introduce concept of resource partitioning, such that femto BS is denied access to RBs that are assigned to MS_u. In other words, the set of RBs allocated to MS_u denoted by \( N_{u0} \) must be left idle by femto BSs. Doing so completely eliminates the interference originating from the culprit femto BS, which, in this case is the dominant source of interference. This increases the SINR (3) achieved at the macro MS_u.

It is possible that more than one macro MS experiences heavy interference from more than one femto BS. Given the set of macro MSs, \( M_{uf} \), that experience heavy interference from the same set of femto BSs, \( F_{uf} \), the resources that are prohibited for \( F_{uf} \) are in the form

\[ N = \cup_{u \in M_{uf}} N_u \]  

(5)

Due to the low femto BS transmit power \( P_f \), it is unlikely that many macro MSs experience heavy interference from the same femto-cell. Hence, only a small subset of the users served by a macro BS are interfered by the same set of femto BSs, \( F_{uf} \), as illustrated in Fig. 1. This implies that the number of RBs \( |N| \gg N \) that must not be used by \( F_{uf} \) is much smaller than the total number of RBs, \( N \in N \), so that the degradation of femtocell capacity is expected to be modest.
D. Interference Mitigation

One major issue of the proposed femto-cell resource partitioning concept is informing a femto-cell about the resources \(\mathcal{N}\) in (5) it must not use. One means to provide a heavily interfering femto BS with the resource allocation \(\mathcal{N}_u\) of the vulnerable macro MSs is by using DL-HII messages, which are analogous to the HII messages specified for uplink inter-cell interference coordination (ICIC) in 3GPP LTE [9, 10]. To this end, an uplink ICIC concept of LTE is adopted for downlink femto-cell resource partitioning in this work. In uplink ICIC for LTE, HII messages are to be sent to those neighbouring macro BSs which cause high interference. In order to tailor the DL-HII messages for each femto BS the following procedure is proposed:

1) A macro MS, \(MS_{\text{src}}\), determines whether it is in close proximity of any femto BSs. This can be done by measurements of reference signal received power (RSRP).
2) The IDs of the corresponding femto BSs, \(\mathcal{F}_{\text{att}}\), are noted at the serving macro BSs.
3) If a macro MS is not allowed to connect to any of the femto BSs in its proximity (closed-access policy), a new DL-HII message is prepared for the interfering \(\mathcal{F}_{\text{att}}\) by the serving macro BS.
4) The macro BS informs \(\mathcal{F}_{\text{att}}\) which RBs \(\mathcal{N}\) are assigned to \(MS_{\text{src}}\).
5) These femto BSs will then refrain from using these RBs, and thus, interference at the vulnerable macro MSs is avoided.

The DL-HII message contains the target cell ID and the allocation vector \(\mathcal{N}_u\) of the vulnerable macro MSs. Since DL-HII messages are intended for specific femto BSs, the messages can be sent directly by macro BSs via the X2 interface, which defines the inter-macro BS information exchange through the wired backbone.

Using DL-HII messages and the X2 interface, a key contribution of this paper is to apply known ICIC methods to a new application; a cellular system with femto-cell underlay. So far, the use of this ICIC method has been limited to interference mitigation between macro-cells. The strength of the proposed algorithm is that existing signalling infrastructure is exploited which is highly relevant for practical implementations.

III. SYSTEM MODEL AND SIMULATION SETUP

A. User Distribution

The simulation area comprises a two-tier, tessellated hexagonal cell distribution. In order to eliminate edge effects with regards to interference, an additional two tiers are simulated. However, statistics are taken only from the first two tiers. Femto-cells have a circular area, each with a fixed radius and they are uniformly distributed over the outermost structure with a given density. A random number of users and one femto BS are uniformly distributed in each femto-cell. In the macro-cell, the macro MSs are uniformly distributed over the entire region. This ensures that there is a certain probability (dependent on femto-cell and macro MS density) that macro MSs lie within femto-cells. Access to femto-cells is restricted to closed subscriber groups, i.e., macro MSs lying within the coverage area of a femto-cell are still served by the macro BS and not the femto BS.

B. Path Loss Models

Three path loss models are used – the urban micro (UMi) model for the macro-cell channel, the indoor hotspot (InH) model for the femto-cell and the indoor-outdoor model to simulate the channel between entities lying indoors and outdoors [11].

1) UMi Model: The UMi model is designed specifically for small cells with high user densities and traffic loads in city centres and dense urban areas. The path loss for the line of sight (LoS) condition is calculated as

\[
PL = \begin{cases} 
22\log_{10}(d_{\text{src}}) + 42 & \text{if } 10\text{m} < d < d_{\text{LoS}} \\
20\log_{10}(f_c [\text{GHz}]) + 90 & \text{if } d_{\text{LoS}} < d < 5\text{km}.
\end{cases}
\]

The effective breakdown distance, \(d_{\text{LoS}}\), is calculated as \(d_{\text{LoS}} = N_{\text{att}} h_{\text{att}}/h_{\text{LoS}} f_c/e\), where \(f_c\) is the centre frequency in Hz, \(e\) is the speed of light and \(h_{\text{att}}\) and \(h_{\text{LoS}}\) are the effective antenna heights for the macro BS and macro MS respectively with values \(h_{\text{att}} = 21\text{ m}\) and \(h_{\text{LoS}} = 0.5\text{ m}\). Log-normal shadowing values are spatially correlated according to the correlation model in [11], where the values of their standard deviations can also be found. The non-LoS model is computed as

\[
PL = 367\log_{10}(d_{\text{src}}) + 40.9 + 20\log_{10}(f_c [\text{GHz}])/5 \quad \text{if } 10\text{m} < d < 2\text{km}.
\]

The LoS probability is a function of distance and is calculated as

\[
P_{\text{LoS}} = \min(\frac{d_{\text{LoS}}}{d}, 1) (1 - e^{-d/36}) + e^{-d/36}.
\]
Selected Publications

2) InH Model: The InH model is used to model the channel for links lying inside the femtocells. The LoS path loss is calculated as

\[ PL = 16.9 \log_{10}(d[m]) + 46.8 + 20 \log_{10}(f_c[\text{GHz}]) \]

if \( 3m < d < 100m \),

The non-LoS model is calculated as

\[ PL = 43.3 \log_{10}(d[m]) + 25.5 + 20 \log_{10}(f_c[\text{GHz}]) \]

if \( 10m < d < 150m \).

Finally, the probability of LoS for a link is computed as

\[ P_{\text{LoS}} = \begin{cases} 1, & d < 4\text{m} \\ \left( \frac{d-4}{d} \right)^2, & 4\text{m} < d < 60\text{m} \\ 0, & d > 60\text{m} \end{cases} \]

3) Outdoor-to-Indoor (and vice-versa) Model: The Urban Micro (UMi) path loss model is used to model only the indoor-to-outdoor path loss and vice versa as

\[ PL = PL_{41} + PL_{d4} + PL_{4i} \]

if \( 50m < d < 5km \).

Here, \( PL_{41} \) is the basic path loss calculated using the UMi model as \( PL_{41} = PL_{UMI}(d_{41}, d_{4i}) \). The parameters \( d_{41} \) and \( d_{4i} \) are calculated as shown in Fig. 2. The parameter \( PL_{d4} \), the loss through the wall, is fixed at \( 20\text{dB} \) and \( PL_{4i} \), dependent on the indoor distance, is calculated as \( PL_{4i} = 0.5d_{4i} \text{dB} \). The delay profiles associated with these path loss models used to generate frequency-selective (fast) fading are provided in [11].

![Fig. 2. Measurement of \( d_{41} \) and \( d_{4i} \) for indoor-to-outdoor path loss calculation.](image)

C. Reuse Concepts

The performance of the system is compared using two different macro-cell frequency reuse schemes, so to vary the amount of macro-cellular interference, as depicted in Fig. 3. In the “full reuse” scheme, each macro-cell utilises the entire bandwidth and transmits with maximum power on all resources in the frequency domain. In contrast, the “hard reuse” scheme is designed such that the entire macro-cell frequency band is divided into three sub-bands. A reuse factor of three is employed, i.e., each macro-cell only utilises a third of the band (one sub-band) and neighbouring cells must use either one of the other two sub-bands. Doing this reduces the amount of interference originating from the tier directly adjacent cells. However, since only a third of the resources are used in any macro-cell, the gain from reduced interference is offset by the reduction in available resources. In any case, femto-cells may always access the entire band apart from the restricted resources imposed by the proposed femto-cell resource partitioning concept.

IV. RESULTS

The simulation is run for a full-buffer traffic model, i.e., all users in the system are active simultaneously. Furthermore, the users in the system are assumed to be static for the duration of the snapshot, so that the effects due to Doppler spread are neglected. Perfect synchronisation in time and frequency is assumed, so that interference between neighboring RBs is avoided. The simulation parameters are listed in Table I.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Femto-cells per macro-cell</td>
<td>5</td>
</tr>
<tr>
<td>Avg. macro BSs per macro-cell</td>
<td>5</td>
</tr>
<tr>
<td>Femto BSs per femto-cell</td>
<td>1-4</td>
</tr>
<tr>
<td>Macro-cell major radius</td>
<td>20m</td>
</tr>
<tr>
<td>Femto-cell radius</td>
<td>10m</td>
</tr>
<tr>
<td>Femto-cell protection radius</td>
<td>20m</td>
</tr>
<tr>
<td>downlink HFD Band</td>
<td>2.6G-2.65 GHz</td>
</tr>
<tr>
<td>Total Number of available RBs</td>
<td>100</td>
</tr>
<tr>
<td>RB Bandwidth</td>
<td>100 kHz</td>
</tr>
<tr>
<td>Thermal Noise per RB</td>
<td>-144dBm</td>
</tr>
<tr>
<td>Macro BS Tx power per RB</td>
<td>24dBm</td>
</tr>
<tr>
<td>Femto BS Tx power per RB</td>
<td>0dBm</td>
</tr>
</tbody>
</table>
Fig. 4. Downlink macro MS capacity for MSs lying within the protection regions of femto-cells.

Fig. 5. Without resource partitioning, the interference originating from femto-cells is almost as much as that originating from macro-cells. However, when resource partitioning is used, the interference originating from femto-cells drops by approximately 20dB.

Fig. 6. Downlink femto-MS capacity for femto-cells having nearby macro-MSs.

The use of resource partitioning is further justified through the results shown in Fig. 5. This figure depicts the levels of interference originating from various sources for macro MSs situated within the protection region of femto-cells for systems using hard and full reuse. The effects of hard reuse are apparent as the macro interference in this case is lower than that for the full reuse case. This is expected since transmission is suppressed on two-thirds of the frequency band. It is seen that, in the absence of resource partitioning, the interference from macro BSs and femto BSs is approximately the same. In the case of macro BSs, the interference comes from BSs other than the one that the macro MS is associated with. In the case of femto BSs, the interference comes from all femto-cells in the system. However, due to the proximity of the macro MS to one (or more) femto-cells, this interference is dominated by the closest femto-cell. Now, if the resource partitioning scheme is put in place, it is seen that the interference originating from femto-cells reduces by approximately 20dB. This is because the interference coming from the nearest femto-cell (which is also the most dominant contributor of the interference) is completely eliminated. This then boosts the capacity achieved at the macro MS and prevents it from going into outage.

The impact of resource partitioning on overall femto-cell downlink performance for femto-cells affected by nearby macro MSs is seen in Fig. 6. It is observed that capacity is higher when the hard reuse scheme is used. This is expected due to the reduced interference originating from macro-cells. More importantly, it must be noted that despite the presence of a macro MS in the vicinity of the femto-cell, even when the femto-cell is banned from using the resources allocated to that MS in the downlink, the achieved user capacity is in the region of 30Mbps (for the full reuse case) and 45Mbps (for the hard reuse case) for the 50th percentile. In the case of full reuse, the femto MS experiences a reduction of approximately 10Mbps when resource partitioning is used. However, despite this,
Fig. 7. Overall downlink femto and macro MS capacity.

very high capacities are achieved inside the femtocell. This indicates that resource partitioning is a viable solution to the downlink femto to macro interference problem since it does not degrade the achievable capacity inside the femtocell to a significant degree while maintaining macro-cell connectivity.

Finally, through Fig. 7, it is demonstrated that the femtocell user capacity remains virtually unchanged even though resource partitioning is used, clearly showing that the benefits of resource partitioning outweigh any drawbacks that it might have. The gain in macro-cell capacity is negligible in this figure because this figure shows the cumulative distribution function (CDF) of capacity for all macro MSs in the system and not just the ones that lie in the vicinity of femtocells as is the case in Fig. 4. For the same reason, the difference between using and not using resource partitioning is greater in Fig. 6 as this figure also highlights the capacities achieved only in the affected femtocells. However, when seen from the point of view of the overall system, it is clear from this figure that while resource partitioning greatly improves service to macro MSs lying in the vicinity of femtocells, it only degrades the overall femto performance marginally. This coupled with the ease with which the concept can be practically realised, highlights the positive impact to be harnessed through resource partitioning.

V. SUMMARY AND CONCLUSION

Femtocell deployment poses a viable complement to cellular networks, Operators need to bear low cost in their deployment, since they are installed directly by the users themselves. Furthermore, since they share both, the radio access scheme and the frequency band with macro BSs, they are compatible with legacy MSs. Aside from these benefits, a cellular network stands to significantly gain in overall system throughput through the widespread deployment of femto BSs. Not only do femto BSs improve indoor coverage, bringing broadband-like experience directly to the handset, but they also offload resources from the macro BS which can be utilised to improve coverage to outdoor users.

It has been seen that in a closed-access system, macro MSs lying in the proximity of femto-cells experience as much interference from femto BSs as they do from macro BSs in the downlink. It has been found that by introducing resource partitioning, the capacity of such macro MSs can be increased by a factor of approximately 5 (at the 50th percentile) by reducing this detrimental interference. The incurred throughput degradation of femto-cells in doing so is minimal, as femto-cells typically lose only a small fraction of their available resources. As femto-users, due to the favourable channel conditions, experience a throughput that is several times the corresponding macro-user throughput, a modest degradation in femto-cell capacity appears acceptable. Therefore, introducing resource partitioning to a closed-access system with femto-cell deployment is a powerful means to retain ubiquitous coverage by macro-cells, as well as to substantially boost the experience of users located indoors.

ACKNOWLEDGEMENT

Initial parts of this work were supported by DFG grant HA 3570/2-1 as part of program SPP-1165 (adaptable heterogeneous communication networks with wireless access – ARKOM) while some later parts of this work have been performed within the framework of the CELTIC project CPS-036 WINNER+

REFERENCES


Category Title

Throughput Enhancement through Femto-Cell Deployment

Zubin Bhariu 1*, Harald Haas 1, Andreas Saut 2 and Gunther Auer 2

1 Institute for Digital Communications, Joint Research Institute for Signal and Image Processing, School of Engineering and Electronics, University of Edinburgh, Edinburgh EH9 3JL, U.K.
2 DOCOMO Euro-Labs, Landberger Strasse 32, 80687 Munich, Germany

SUMMARY

This paper studies the impact of a femto-cell underlay deployment that shares radio frequency resources with urban macro-cells. Due to their random and uncoordinated deployment, femto-cells potentially cause destructive interference to macro-cells and vice-versa. On the other hand, femto-cells promise to substantially enhance the spectral efficiency due to an increased reuse of radio resources. The performance of networks with indoor Home Evolved NodeB (HeNB) deployment is compared to a system where all users, including indoor users, are served by the outdoor macro Evolved NodeB (eNB). In addition, the impact of closed-access and open-access femto-cell operation is examined. It is demonstrated that significant capacity gains can be achieved through such HeNB deployment, regardless of whether closed-access or open-access is considered. Results clearly indicate that the capacity gains through femto-cell deployment outweigh the additional interference they introduce. Copyright © 2010 AET

1. INTRODUCTION

The rapidly increasing demand for increased user and system capacity in wireless networks is served by higher bandwidth allocation, but since bandwidth is scarce and expensive, a key to substantial capacity enhancement is to improve the spatial reuse of radio frequency resources. One of the most powerful methods of boosting wireless capacity is by shrinking the cell size. The reason for this is that smaller cell sizes effectively increase spatial reuse of spectrum [1]. The shorter transmission distances enhance link capacity due to higher channel gains [2]. While decreasing the cell size boosts system capacity, the cost involved is becoming increasingly prohibitive due to the required installation of new network infrastructure.

Studies indicate that a large proportion of data traffic originates indoors [3]. Poor signal reception caused by high penetration losses through walls severely compromises the operation of indoor broadband data services. Thus, the concept of femto-cells has recently attracted considerable interest. 3rd generation (3G) femtocells are currently discussed in standardisation bodies, such as 3GPP Long Term Evolution (LTE). Femto-cells consist of user-deployed HeNBs, which are cheap, low-power, plug-and-play base stations. HeNB deployment extends and improves macro-cell coverage indoors. As HeNBs are connected to the backbone network via cable, they offload indoor users from the macro-cell, thus potentially enhancing the capacity both indoors as well as outdoors.

A number of proposals have been made in recent years to increase indoor capacity. In [4], it has been proposed that buildings be equipped with distributed antennas in order to improve coverage. However, the implementation of this system requires careful planning. The proposal in [5] calls for the separation of user equipments (UEs) based on their mobility classes and serving them within micro and macro-cell accordingly. This proposal requires dual-mode UEs since different access methods are used, based on the mobility class within which the UE falls. In [6-9], the authors propose the TDD underlay concept.
Owing to the asymmetric nature of traffic, the underloaded frequency division duplex (FDD) band can be split in time such that the HeNB transmits and receives information from its associated UEs in a time division duplex (TDD) fashion. In this paper, both macro and femto-cell operate in the same radio frequency spectrum in FDD mode, compliant with 3GPP specifications [10]. The HeNB backhauls data on a wired interface to the cellular operator network. Through femto-cell deployment, the operator is able to concentrate on providing better service to the outdoor macrocell UEs. Another benefit for operators is that broadband coverage is extended to the indoor environment.

However, HeNBs are deployed without network planning. Since HeNBs operate on the same bands as macrocell eNBs, their deployment introduces additional interference [11]. Furthermore, questions regarding security and access to the femto-cell are raised with the deployment of HeNBs. The discussion is therefore taken in the direction of open-access versus closed-access systems. Open-access allows any UE to connect to the HeNB, whereas closed-access only allows a specified set of UEs to connect to the HeNB. Closed-access systems are therefore more likely to impose high interference to indoor UEs that lie in close vicinity of a femto-cell, but are not connected to a HeNB.

One of the first studies on femto-cells [12] investigates the geographic distribution of throughput for a deployment of open-access femto-cells in a cellular network. The impact of HeNB deployment on macrocell performance is analyzed in [13]. The focus of the work presented in this paper is to conduct a rigorous assessment of the impact of femto-cell deployment on a traditional cellular network. We also analyze the differences between open and closed-access systems through extensive system-level simulations. A system without HeNB deployment, where all users (indoors or outdoors) are exclusively served by macrocell eNBs (as in a traditional cellular system) serves as the benchmark system for comparison. Systems with HeNB deployment are distinguished between open and closed-access. We demonstrate that HeNB deployment, regardless of the access method, has a clear advantage over the benchmark system in terms of user and overall system capacity.

The remainder of this paper is organized as follows. Section 2 describes the system model and simulator setup. Simulation results are presented in Section 3 and Section 4 highlights the key findings.

2. SYSTEM MODEL AND SIMULATION SETUP

The system bandwidth B is divided into N resource blocks (RBs), B = NB, where the RB represents the basic orthogonal frequency division multiple access (OFDMA) time-frequency unit. The set of available RBs, N, with cardinality |N| = N, is distributed uniformly by eNBs among their associated macro UEs. Within the femto-cells, for closed-access systems, the HeNB allocates all RBs to the femto UE. In the case of open-access systems, if additional UEs from the macro-cell are assimilated into the femto-cell, the RBs are uniformly distributed among all the UEs served by that HeNB. The received signal power observed by UEu (where u is the user index) at RB n is given by

\[ Y_u^n = G_{n}^{\text{HeNB}} P_{m} + P_{f} + \eta \]  

where \( G_{n}^{\text{HeNB}} \) is the channel gain between \( \text{HeNB} \) and its serving HeNB or eNB, and \( P_{f} \) accounts for the interference observed at RB \( n \). The thermal noise per RB is represented by \( \eta \). The transmit power is set to \( P_{m} = P_{f} \) if UEu is served by an eNB and HeNB, respectively.

2.1. Interference and Spectral Efficiency Calculation

Universal frequency reuse is assumed such that the every macro and femto-cell utilizes the entire system bandwidth, \( B \). As macro and femto-cell share the available time-frequency resources, the aggregate interference, \( I_{a}^{\text{HeNB}} \), is composed of macro and femto-cell interference

\[ I_{a}^{\text{HeNB}} = \sum_{n \in \text{HeNB}} G_{n}^{\text{HeNB}} P_{m} + \sum_{j \in \text{RB}} G_{j}^{\text{HeNB}} P_{f} \]  

where \( G_{n}^{\text{HeNB}} \) accounts for the channel gain between interferer j observed by UEu. The sets of macro and femto-cell interfering eNBs and HeNBs are denoted by \( \mathcal{M}_{\text{HeNB}} \) and \( \mathcal{F}_{\text{HeNB}} \), respectively. In the downlink, a UE suffers from interference from neighbouring HeNBs and eNBs. Likewise, in the uplink, a HeNB experiences interference from macro and femto UEs in adjacent cells. In particular, for closed-access systems, macro UEs lying within the coverage of a femto-cell are exposed to severe femto interference by the HeNB in the downlink, while HeNBs lying within the coverage of macro UEs are exposed to severe macro interference in the uplink. Fig. 1 highlights how the interference situations change for different access modes. The signal-to-interference-plus-noise ratio (SINR) observed at UEu amounts to

\[ \gamma_{u} = \frac{G_{u}^{\text{HeNB}} P_{m}}{I_{a}^{\text{HeNB}} + \eta} \]  

Given the SINR and the number of served RBs, \( |N_{u}| \), the capacity \( C_{u} \) of UEu is calculated by using the Shannon bound

\[ C_{u} = \sum_{n \in N_{u}} B \log_{2} \left( 1 + \frac{\gamma_{u}}{1} \right) \]  

where \( N_{u} \) is the set of RBs allocated to UEu. For a macro UE, \( N_{u} = N_{v} \), unless the macro-cell contains only one UE.
which is highly unlikely. For a closed-access femto-cell, if the HeNB serves only one femto UE, \( N_U = N \), and in the open-access case, if the femto-cell contains a foreign macro UE in addition to the femto UE, again, \( N_U < N \).

2.2. Uplink Power Control

Power control is applied in the uplink in both, the femto and macro layer. According to [14], the transmit power per RB for a UE, \( P_{RB, UE} \), is adjusted as a function of the combined uplink path loss and shadowing, \( L_{tot} \), as

\[
P_{RB, UE} = \min \left\{ P_{\text{trans}}, \max \left[ P_{\text{min}}, \frac{P_{\text{trans}} \times \left( \frac{L_{tot}}{\alpha} \right)}{\epsilon} \right] \right\}
\]

where \( P_{\text{trans}} \) is the maximum transmit power per RB, \( P_{\text{trans}} \) is the minimum transmit power per RB and \( \alpha \) is the \( \alpha \)-percentile path loss, a constant whose value determines the critical path loss value above which a UE transmits with full power. This balancing factor \( \epsilon \) determines how steeply the transmit power increases with increasing path loss. In the femto layer, the maximum femto UE transmit power is set such that it cannot be higher than the HeNB transmit power.

2.3. Channel Model

The channel gain, \( G_{ni}^{t,r} \), between a transmitter \( t \) and a receiver \( r \) on RB \( n \) as defined in (1), is composed of distance dependent path loss, log-normal shadowing and the channel variations due to frequency-selective fading and is calculated as

\[
G_{ni}^{t,r} = |H_{ni}^{t,r}|^2 10^{-L_{dist}(d)/10} 10^{-\sigma_n d_x^X / 10},
\]

where \( H_{ni}^{t,r} \) accounts for the channel transfer function on RB \( n \) between transmitter \( t \) and receiver \( r \), \( L_{dist}(d) \) is the distance-dependent path loss (in dB), and \( \sigma_n \) is the log-normal shadowing value (in dB) with standard deviation \( \sigma \), as described in [15]. While the channel response, \( H_{ni}^{t,r} \), generally exhibits time and frequency dispersions, channel fluctuations within a RB are neglected because the RB dimensions are significantly smaller than the coherence time and coherence frequency of the channel [16]. The delay profiles associated with the applicable propagation conditions that generate frequency-selective fading of \( H_{ni}^{t,r} \) are provided in [15, 17].

2.4. Path Loss Models

Three path loss models (along with their respective delay profiles) as described in [15, 17] are used—the urban micro (UMi) model for the macro-cell channel, the indoor hotspot (InH) model for the femto-cell channel and the indoor-to-outdoor model to simulate the channel between entities lying indoors and outdoors. For each link in the system, the probability of line of sight (LoS) is calculated as specified in the appropriate path loss model, and based on the LoS condition the associated path loss model is applied to the respective link. Furthermore, a wall penetration loss is considered for the outdoor-to-indoor links.

2.4.1. UMi Model

This model is designed specifically for small cells with high user densities in dense urban areas. The path loss for the LoS condition is calculated as (9). Here, the distance between transmitter and receiver is \( d \), the effective breakpoint distance is calculated as \( r_{E} = \frac{4 H_{CMB} h_{CMB}}{c} \), where \( f_c \) is the centre frequency in Hz, \( c \) is the speed of light in m/s and \( h_{CMB} \) and \( H_{CMB} \) are the effective antenna heights for the eNB and UE, respectively.

\[
L_{LoS} = 40 + 20 \log_{10} \left( \frac{d}{r_{E}} \right)
\]

The non-LoS model is computed as (8).

\[
L_{non-LoS} = 40 + 20 \log_{10} \left( \frac{d}{r_{E}} \right) + 20 \log_{10} \left( r_{E} \right)
\]

2.4.2. InH Model

This model is used to model the channel for indoor links. The LoS path loss is calculated as (9) and the non-LoS model is calculated as (10). Finally, the probability of LoS for a link is computed as

\[
Pr(LoS) = \begin{cases} 
1; & d \leq 4, \\
1 - e^{-e^{-d/4}}; & 4 < d < 60, \\
e^{-e^{-d/4}}; & d \geq 60.
\end{cases}
\]

Copyright © 2010 AETT

Prepared using AETTLaTeX


DOI: 10.1002/ett
2.4.3. Outdoor-to-Indoor (and vice-versa) Model

The UMi path loss model is used to model only the indoor-to-outdoor path loss and vice-versa.

\[ L_{\text{UMI}} = \left\{ \begin{align*} & 22 \log_{10}(d_m) + 42 + 20 \log_{10}(f_c [\text{GHz}]/5); \quad \text{10m} < d_m < d_{\text{WP}}, \\ & 40 \log_{10}(d_m) + 92 - 18 \log_{10}(k_{\text{NB}}) \\ & - 18 \log_{10}(d_{\text{UE}}) + 20 \log_{10}(f_c [\text{GHz}]/5); \quad d_{\text{WP}} < d_m < 5 \text{km}. \end{align*} \right. \]

\[ L_{\text{UMI}} = \left\{ \begin{align*} & 36.7 \log_{10}(d_m) + 40.9 + 25 \log_{10}(f_c [\text{GHz}]/5); \quad \text{10m} < d_m < 2 \text{km}, \\ & 16.9 \log_{10}(d_m) + 46.8 + 20 \log_{10}(f_c [\text{GHz}]/5); \quad 3 \text{m} < d_m < 100 \text{m}, \\ & 43.3 \log_{10}(d_m) + 25.5 + 20 \log_{10}(f_c [\text{GHz}]/5); \quad 10 \text{m} < d_m < 150 \text{m}. \end{align*} \right. \]

Here, \( L_{\text{UMI}} \) is the basic path loss calculated using the UMI model as \( L_{\text{UMI}} = L_{\text{UMI}}(d_{\text{out}} + d_{\text{in}}) \). The parameter \( d_{\text{out}} \) refers to the distance between the femto-cell wall and the outdoor eNB/UE and \( d_{\text{in}} \) refers to the indoor distance between the UE/HeNB and the femto-cell wall. The parameter \( L_{\text{WP}} \) is the wall penetration loss and \( L_{\text{WP}} \), dependent on the indoor distance alone, is calculated as \( L_{\text{WP}} = L_{\text{WP}}(d_{\text{in}}) \). In this case, the probability of LoS is zero.

2.5. User Distribution

The simulation area is a two-tier, tessellated hexagonal cell distribution. In order to eliminate edge effects, two additional tiers are simulated, however, statistics are taken only from the first two tiers. Femtocells have a circular area, each with the same radius, and they are uniformly distributed with a given density. One femto UE and one HeNB are randomly distributed in each femto-cell.

In the macrocell, UEs are randomly distributed over the entire area. These UEs are served by the macro-cell eNB. Depending on their density and the density of femto-cells there is a certain probability (approximately 6%) that some of these UEs lie within a femto-cell. In the case of open-access systems, such UEs are assimilated into the femto-cell and served by the HeNB. For comparison, we also consider a benchmark system where all UEs are served by the macrocell (whether located indoors or outdoors).

Once the users are distributed, log-normal shadowing maps containing correlated shadowing values in space are generated. Using these and the scenario specific path loss models described in Section 2.4, macro UEs are associated with the eNB to which they have the least path loss. Depending on whether open or closed-access is considered, macro UEs that lie within femtocells are either assimilated or left to communicate with the eNBs.

<table>
<thead>
<tr>
<th>Table 1. Simulation Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>Avg. femto-cells per macro-cell</td>
</tr>
<tr>
<td>Avg. macro UEs per macro-cell</td>
</tr>
<tr>
<td>Femto UEs per femto-cell</td>
</tr>
<tr>
<td>Inter-site distance</td>
</tr>
<tr>
<td>Femtocell radius</td>
</tr>
<tr>
<td>Bandwidth</td>
</tr>
<tr>
<td>Uplink FDD Band</td>
</tr>
<tr>
<td>Downlink FDD Band</td>
</tr>
<tr>
<td>Total number of available RBs</td>
</tr>
<tr>
<td>RB Bandwidth</td>
</tr>
<tr>
<td>Thermal Noise</td>
</tr>
<tr>
<td>Total eNB Tx power</td>
</tr>
<tr>
<td>Total HeNB Tx power</td>
</tr>
<tr>
<td>Max. macro UE Tx power</td>
</tr>
<tr>
<td>Max. femto UE Tx power</td>
</tr>
<tr>
<td>Min. macro/femto UE Tx power</td>
</tr>
<tr>
<td>Wall penetration loss, ( L_{\text{WP}} )</td>
</tr>
<tr>
<td>k-percentage path loss, ( \alpha )</td>
</tr>
<tr>
<td>Path Loss Balancing factor, ( \xi )</td>
</tr>
</tbody>
</table>

3. RESULTS

Simulations are run for a full-backhaul traffic model. Perfect synchronisation in time and frequency is assumed so that interference between neighbouring RBs is avoided. The parameters used in the simulation are taken from the 3GPP specifications [10, 18–21] and are shown in Table 1.

The sum system capacity in the uplink and downlink, normalised per macro-cell, is depicted in Fig. 2. The benefit of femto-cell deployment is clearly demonstrated here. The normalised sum system capacity is generated as the sum of the individual user capacities, divided by the number of macro-cells considered. For systems with HeNB deployment, the aggregate femto and macro user capacity is computed against the benchmark system where all users are served by the eNB. These results highlight the achieved gains through HeNB deployment. It is seen that the sum capacity for systems with HeNB deployment
deployment is more than two orders of magnitude higher than that for the benchmark system in both the uplink and downlink. Certainly, without femto-cells, the benchmark system experiences the least interference in most cases, e.g., Figs. 4(a) and 6(a). However, these gains are offset by the fact that in the benchmark, the indoor users are not offloaded from the eNB. Since the same set of resources are available to the eNBs in all systems, each user, on average, gets allocated fewer resources in the benchmark system. These results illustrate how resources in a macro-cell can be effectively reused by femto-cells to significantly boost the overall system capacity. A higher transmit power in the downlink results in an improved SINR at the femto UE. Despite the higher interference this causes to macro UEs, the sum capacity increases with increased HeNB transmit power. Due to the severe wall penetration losses the increased transmit power results in a lower increase in interfering power than useful power. In the uplink, due to power control, the transmit power values are typically below the maximum power. Thus, the uplink performance is independent of the maximum HeNB power. In the benchmark system, since HeNBs do not exist, the capacity remains constant regardless of the HeNB transmit power.

Before proceeding with the remaining results we define:

**Set A:** All femto UEs in the system.

**Set B:** All macro UEs in the system, regardless of whether they lie indoors or outdoors.

**Set C:** Those macro UEs lying inside femto-cells.

Furthermore, macro UEs may lie indoors as well as outdoors. Femto UEs strictly lie indoors.

### 3.1. Downlink

The downlink capacity for Set A for varying HeNB transmit powers is shown in Fig. 3. It is observed that an increase in HeNB transmit power improves downlink user capacity for both open and closed-access. This is expected, since the increased transmit power results in an increased SINR at the receiver. Furthermore, closed-access systems outperform open-access systems. This is attributed to the fact that in case of open-access, macro UEs that are located within the coverage of the HeNB will get assimilated into that femto-cell. In this case, the HeNB must distribute the available resources among the femto UEs and the assimilated UE, thus resulting in each UE getting allocated fewer RBs compared to closed-access.

Fig. 4(a) shows the interference experienced by Set B for open and closed-access systems as well as for the benchmark system. The cumulative distribution function (CDF) for the benchmark system shows three distinct sections. The lowest interference regime spanning between -118 and -130 dBm corresponds to the interference experienced by indoor users. The middle portion corresponds to non-LoS interference experienced by outdoor users and the last portion represents LoS interference experienced by outdoor users. The systems with femto-cell deployment are exposed to significantly more interference, since, unlike the benchmark system, most macro UEs are located outdoors, and outdoor UEs are not protected by building walls. Clearly, the higher the HeNB transmit power, the greater is the interference experienced by macro UEs. For closed-access, some indoor UEs are considered in the interference CDF. These experience less macro interference, so that their interference CDF is superior to open-access at low HeNB transmit power. For high HeNB transmit power, femto interference dominates indoors and closed-access performance becomes worse.

Since also the intended signal received from an eNB is strongly attenuated indoors and the amount of assigned resources per user differs, the user capacity should be considered for a fair comparison. Fig. 4(b) depicts the CDF of user capacity for Set B in the downlink. Here, the lower the HeNB transmit power, the better the downlink performance of the UEs. This is expected since the amount of interference originating from femto-cells is directly proportional to the HeNB transmit power. For this reason, the best macro performance is achieved when
the HeNB transmit power is at its lowest, i.e., $-30$ dBm. It is interesting to note that the systems with femto-cell deployment significantly outperform the benchmark system. This is due to the lower spatial reuse in the benchmark system, which means that the eNB has to share the available resources with a higher number of users. In this setting, with 15 femto-cells per macro-cell on average, each femto-cell serving one UE, eNBs in the benchmark system need to serve more than twice the number of macro UEs, giving rise to poor benchmark user capacities.

### 3.2. Uplink

Fig. 5 shows the CDF of Set A uplink capacity. It is observed that the UEs achieve very high capacities within the femto-cells. Furthermore, closed-access slightly outperforms open-access systems. This somewhat surprising result is attributed to the fact that in case of open-access, macro UEs that are located within the coverage of the HeNB will get assimilated. In this case, the HeNB must distribute the available resources among the femto UEs and the assimilated UE, thus resulting in each UE getting allocated fewer RBs. This overcompensates the increased interference femto HeNBs experience from macro UEs. The difference in overall capacity between open and closed-access is negligible, since the probability that a macro UE lies indoors is low. It must be noted that due to the very short transmit distances within femto-cells, the power control scheme in the uplink forces almost all UEs served by a HeNB to transmit with the lowest possible power ($-30$ dBm). This can be seen in Fig. 5, where the performance is very similar to the $-30$ dBm performance observed in Fig. 5.

Fig. 6(a) shows the uplink interference experienced by Set B UEs. It is seen that that the trends of uplink interference are substantially different from those of downlink interference. As macro UEs are served by eNBs regardless of whether femto-cells are deployed or not, since all eNBs lie outdoors and interference is measured at the eNB, the corresponding CDFs do not exhibit such pronounced multi-modal distributions. There is no significant difference between open and closed-access, because UEs that get assimilated into open-access femto-cells are classified as Set A UEs, and the uplink interference their HeNBs experience is not reported in this figure. Similar to Fig. 4(a), the benchmark system exhibits the least interference, due to the lack of femto-cells.

Fig. 6(b) shows the uplink capacity CDF of Set B. The performance of the benchmark system is plotted for comparison. As expected, open-access outperforms closed-access, since macro UEs lying within femto-cells get assimilated. This has a double impact on macro performance: 1) these UEs get offloaded from the macro-cell, thus freeing up resources, and 2) this user experiences a boost in capacity because the wall penetration losses are circumvented, transmission distances are reduced, and strong femto-cell interference is avoided. However, the actual performance difference is small.

### 3.3. Set C: Affected Macro User Performance

Figs. 7(a) and 7(b) show the uplink and downlink capacities of Set C in closed-access and open-access
Selected Publications

Throughput Enhancement through Femto-Cell Deployment

Figure 6. Uplink interference per RB (a) and capacity statistics (b) for Set B.

(a) Set B uplink interference.
(b) Set B uplink capacity.

Figure 7. Capacity statistics for Set C in closed-access (a) and open-access (b).

(a) Capacity of Set C in closed-access systems.
(b) Capacity of Set C in open-access systems.

Figure 8. Downlink interference statistics for Set C.

It is seen from this figure that in the case when the HeNB transmit power is at its highest, i.e., 20 dBm, the difference in interference between open and closed-access systems is greater than 96 dB. For open-access, since the interference is below the thermal noise floor, such a system is no longer interference-limited, but noise-limited.

Copyright © 2010 AETT
Prepared using etaluth.cls

DOI: 10.1002/ett

170
4. CONCLUSIONS AND FUTURE WORK

Femtocell deployment poses a viable complement to cellular networks. Operators need to bear low cost in their deployment since they are installed directly by the users themselves. Furthermore, since they share both the radio access scheme and the frequency band with eNBs, they are compatible with legacy UEs. Hence, from these benefits, a cellular network stands to significantly gain in overall system throughput through the widespread deployment of HeNBs. Not only do HeNBs improve indoor coverage, bringing wireless broadband-like experience directly to indoor environments, but they also offload resources from the eNB, which can be utilised to improve coverage to outdoor users.

In terms of overall throughput, under the assumption of the femtocell's density used in this work, the difference between closed-access and open-access systems is almost negligible because of the relatively low probability that a macro UE lies inside a femto-cell. However, if a macro UE lies within a femto-cell, it might not be able to receive a downlink transmission from its eNB because of high signal attenuation and, more importantly, very high interference from the nearby HeNB. If a closed-access femto-cell happens to contain a macro UE, there has to be a method of nullifying the downlink interference experienced by this macro UE, or else it will almost certainly go into outage. In this context, smart resource allocation techniques or power control for femto-cells is an open avenue for further research. Furthermore, it has been shown in this paper that from the macro UEs viewpoint in closed-access systems, the downlink direction is the critical traffic direction. Similarly, from the femto-UEs viewpoint in open-access systems, the uplink direction is critical. Therefore, depending on whether priority lies with the macro or femto-cell, research on closed-access systems must be devoted to mitigate uplink interference imposed on femto-UEs, or downlink interference caused by closed-access HeNBs.

ACKNOWLEDGEMENTS

Initial parts of this work were supported by DFG grant HA 357/5-1 part of program SAT-163 (adaptability in heterogeneous communication networks with wireless access – ACKOM) while some latter parts of this work have been performed within the framework of the CELTIc project CP5-026 WINNER++.

REFERENCES


Copyright © 2010 AETT
Prepared using etlife/PLCS

171
Dynamic Resource Partitioning for Downlink Femto-to-Macro-Cell Interference Avoidance

Zubin Bharucha*, Andreas Saul†, Gunther Auer‡ and Harald Haas*

*Institute for Digital Communications
Joint Research Institute for Signal and Image Processing
School of Engineering and Electronics
The University of Edinburgh
EH9 3JL, Edinburgh, UK
{z.bharucha, h.haas}@ed.ac.uk

†DOCOMO Euro-Labs
80687 Munich, Germany
{saul, auer}@docomolab-euro.com

Abstract

Femto-cells consist of user-deployed Home Evolved NodeBs (HeNBs) that promise substantial gains in system spectral efficiency, coverage and data rates due to an enhanced reuse of radio resources. However, reusing radio resources in an uncoordinated, random fashion introduces potential destructive interference to the systems, both in the femto and macro layers. An especially critical scenario is a closed-access femto-cell with co-channel deployment to the macro-cell, which imposes strong downlink interference to nearby macro user equipments (UEs) that are not permitted to hand over to the femto-cell. In order to maintain reliable service of macro-cells, it is imperative to mitigate the destructive femto-cell to macro-cell interference. The contribution in this paper focuses on mitigating downlink femto-cell to macro-cell interference through dynamic resource partitioning, in the way that HeNBs are denied access to downlink resources that are assigned to macro UEs in their vicinity. By doing so interference to the most vulnerable macro UEs is effectively controlled at the expense of a modest degradation in femto-cell capacity. The necessary signalling is conveyed through downlink high interference indicator (DL-HII) messages over the wired backbone. Extensive system level simulations demonstrate that by using resource partitioning, for a sacrifice of 4% of overall femto downlink capacity, macro UEs exposed to high HeNB interference experience a ten-fold boost in capacity.
I. INTRODUCTION

There is a growing demand for increased user and system throughput in wireless networks. Naturally, such rapidly increasing demand is served by higher bandwidth allocation, but since bandwidth is scarce and expensive, a key to substantial throughput enhancement is to increase the spatial reuse of radio frequency resources. One powerful method of boosting wireless capacity is by shrinking the cell size. The reason for this is that smaller cell sizes enable a more efficient spatial reuse of spectrum [1]. Furthermore, the shorter transmission distances enhance link capacity due to higher channel gains [2].

Studies indicate that a significant proportion of data traffic originates indoors [3]. Poor signal reception caused by penetration losses through walls severely hampers the operation of indoor data services in state-of-the-art systems. Recently, the concept of 3rd generation (3G) and beyond 3G (B3G) femto-cells, in which HeNBs are placed indoors, has therefore attracted considerable interest. HeNBs are low-cost, low-power, short-range, plug-and-play base stations that are directly connected to the backbone network. HeNBs aim at extending broadband coverage to authorized UEs located indoors where it is most needed [3]. HeNBs therefore offload indoor users from the macro-cell, thus potentially enhancing the capacity both, indoors by bypassing wall penetration losses, as well as outdoors by freeing up resources [4], [5]. Moreover, femto-cell deployment could potentially lead to an overall reduced energy consumption as penetration losses due to walls are circumvented [6].

In [7]-[9], the authors propose the TDD underlay concept. Owing to the asymmetric nature of traffic [10], one of the frequency division duplex (FDD) bands (the underloaded one) can be split in time such that the HeNB transmits and receives information from its associated UE in a time division duplex (TDD) fashion. This work has been extended in [11] where the TDD underlay concept is applied to multihop networks in which the HeNB is linked to the Evolved NodeB (eNB) in a two-hop fashion. The other FDD band is entirely used (in time) by the eNB to relay information to the HeNB. This proposal, while making efficient utilisation of unused resources, still encounters a bottleneck because typically, the link between the HeNB and its femto UEs is much stronger than that between the eNB and the macro UE.

In this paper, both macro and femto-cells are assumed to operate in the same radio frequency spectrum in FDD mode, compliant with the specifications for B3G mobile communication systems [12]. Like in the original TDD underlay concept [7], the HeNB backhauls data through a dedicated broadband gateway (DSL/cable/Ethernet/etc.) to the cellular operator network.

However, HeNBs are deployed without network planning, such that their deployment introduces ad-
ditional interference [13]. Regarding hand-over between macro and femto-cells, two access control mechanisms, open-access and closed-access, are identified. In open-access femto-cells, macro UEs get assimilated into the femto-cell, which means that UEs that lie within the coverage area of a femto-cell are handed over to the corresponding HeNB. In closed-access systems the HeNB only grants access to a particular set of authorised UEs. It is these closed-access systems that cause (and receive) the most detrimental interference. This is because a "foreign" macro UE lying in the coverage area of a femto-cell is not allowed to communicate with the HeNB, but must communicate with the eNB that lies outdoors. Due to wall penetration losses, such macro UEs receive a highly attenuated signal from the eNB and, in addition, receive excessive interference originating from the HeNBs whose coverage areas the macro UE lies in. No matter the access control, it is crucial that the provision of base-coverage by the macro-cell network is not compromised by femto-cell deployment.

In [14], the feasibility of the co-existence of co-channel macro and femto-cells has been investigated. A power control method is defined in the downlink such that a constant femto-cell radius is maintained. In [15], the authors analyse the impact of femto-cell deployment on the macro-cell performance. In all of these papers, no active interference avoidance technique is discussed. In [16], the authors analyse the uplink capacity and interference avoidance for networks consisting of macro and femto-cells existing together in a code division multiple access (CDMA) network. In particular, the authors evaluate a network-wide area spectral efficiency metric, which is defined as the feasible combinations of the average number of macro-cell UEs and HeNBs per eNB that satisfy a target outage constraint. Interference avoidance in this case is done via a time-hopped CDMA physical layer and sectorization of antennas. In contrast to the above, the contribution in this paper comes in the form of a novel dynamic downlink interference avoidance technique which prioritizes macro UEs for a spectrum sharing orthogonal frequency division multiple access (OFDMA) system. The reason for this is twofold. First, the downlink is more critical in terms of femto-to-macro interference, because it is more likely that a macro UE suffers from downlink interference from a nearby HeNB than an eNB suffers from uplink interference from a femto UE due to the asymmetry in cell size, and the corresponding asymmetry in transmit powers, between macro and femto-cells. Second, priority should generally be given to the macro layer rather than the femto layer. To this end, if a HeNB is perceived to interfere severely with a macro UE, it must act so as to nullify this interference by smartly scheduling (partitioning) its resources. If no macro UE is affected, the femto-cell uses all resources (full frequency reuse).

For the B3G mobile communication system 3rd generation partnership project (3GPP) Long Term Evolution (LTE) [12], high interference indicator (HII) messages are specified to deal with macro-to-macro
interference in the uplink [17], [18], which are conveyed through the X2 interface via the wired backbone. In this work, it is demonstrated that the same framework can be applied for downlink interference coordination between macro and femto-cells, by signalling downlink high interference indicator (DL-HI) messages via an X2 interface to femto-cells.

In order to assess the impact of resource partitioning on macro and femto-cell performance, system level simulations are carried out. The performance of a closed-access system is compared against the performance of the same distribution of users using the aforementioned resource partitioning scheme. For comparison purposes, a benchmark system is simulated which closely reflects state-of-the-art cellular networks in which there are no HeNBs, and all femto UEs are served by eNBs.

II. SYSTEM AND CHANNEL MODEL

The downlink of an OFDMA system is considered, where the system bandwidth $B$ is divided into $N$ resource blocks (RBs), $B = NB_{RB}$. A RB represents one basic time-frequency unit with bandwidth $B_{RB}$. All eNBs transmit with a fixed power per RB, $P_{e}$, and all HeNBs transmit with a fixed power, $P_{f}$, per RB. Perfect synchronisation in time and frequency is assumed.

Universal frequency reuse is considered, so that both macro and femto-cells utilise the entire system bandwidth $B$. Multiple receive antennas are assumed, and the $M$ received signal streams are combined with maximum ratio combining (MRC). The gain from MRC is approximated by simulating $M$ individual, uncorrelated receive streams and adding the achieved signal-to-interference-plus-noise ratio (SINR) [19]. The set of available RBs $\mathcal{N}$, with cardinality $|\mathcal{N}|=N$, is distributed by eNBs and HeNBs among their associated macro and femto UEs respectively. Throughout this paper, $u$ is used to identify any macro or femto UE and $v_u$ denotes the HeNB which serves UE $u$. The received signal power observed by UE $u$ at RB $n$ is given by

$$ Y_{in}^u = P_{in} \sum_{m} G_{in,m}^{u} + I_{in}^{u} + \eta, $$

where $G_{in,m}^{u}$ is the channel gain between UE $u$ and its serving HeNB or eNB $v_u$, observed at receive antenna $m$ and at RB $n$. Furthermore, $\eta$ accounts for thermal noise per RB which is constant across all RBs. The transmit power is set to $P_{e}=P_{m}$ and $P_{f}=P_{f}$ if UE $u$ is served by an eNB or HeNB, respectively. The aggregate interference $I_{in}^{u}$ is composed of macro and femto-cell interference

$$ I_{in}^{u} = \sum_{m} \left\{ \sum_{v \in \mathcal{M}_{\text{f}} \cap \mathcal{F}_{\text{f}}} G_{in,m}^{v} P_{in} + \sum_{v \in \mathcal{F}_{\text{f}}} G_{in,m}^{v} P_{f} \right\}, $$

where the first and second addends represent the macro and femto-cell interference, respectively. The set of interfering eNBs and HeNBs are denoted by $\mathcal{M}_{\text{f}}$ and $\mathcal{F}_{\text{f}}$. In case UE $u$ is served by an eNB $v_u$. 

December 31, 2009
\( M_{\text{int}} \) comprises all eNBs except for \( v_{\text{int}} \) i.e., \( v_{\text{int}} \notin M_{\text{int}} \). In this case, \( F_{\text{int}} \) is the set of all HeNBs in the system. Likewise, if UE \( u_{i} \) is served by a HeNB \( v_{\text{int}} \), then \( v_{\text{int}} \notin F_{\text{int}} \). The SINR observed by UE \( u_{i} \) at RB \( n \) amounts to

\[
\gamma_{n}^{u_{i}} = \frac{P_{\text{dB}} \sum_{m=0}^{M} G_{m}^{v_{\text{int}}}^{u_{i}}}{I_{n}^{m} + \eta}.
\] (3)

Due to MRC at the receiver, the channel gains \( G_{m}^{v_{\text{int}}}^{u_{i}} \) add constructively, so that the average SINR is increased by a factor of \( M \), together with an \( M \)-fold diversity gain.

Link adaptation is implemented where the modulation and coding scheme used are selected based on the achieved SINR. In order to model link adaptation, the SINR is mapped to the capacity using the attenuated and truncated Shannon bound method \[20\]. Given a particular SINR \( \gamma_{n}^{u_{i}} \), the spectral efficiency on RB \( n \) for UE \( u_{i} \), \( C_{n}^{u_{i}} \), is determined by

\[
C_{n}^{u_{i}} = \begin{cases} 
0 & \text{for } \gamma_{n}^{u_{i}} < \gamma_{\text{min}} \\
\alpha S(\gamma_{n}^{u_{i}}) & \text{for } \gamma_{\text{min}} < \gamma_{n}^{u_{i}} < \gamma_{\text{max}} \\
C_{\text{max}}^{u_{i}} & \text{for } \gamma_{n}^{u_{i}} \geq \gamma_{\text{max}}
\end{cases}
\] (4)

where \( S(x) = \log_{2}(1 + x) \) in [bit/s/Hz] is the Shannon bound, \( \alpha \) is the attenuation factor representing implementation losses and \( \gamma_{\text{min}} \) and \( \gamma_{\text{max}} \) are the minimum and maximum SINRs supported by the available modulation and coding schemes. These parameters are summarized in Table I. The capacity \( C_{u_{i}} \) of UE \( u_{i} \) is then calculated as the aggregate capacity on all the RBs allocated to it as

\[
C_{u_{i}} = B_{\text{RB}} \sum_{n \in \mathcal{N}_{u_{i}}} C_{n}^{u_{i}},
\] (5)

where \( \mathcal{N}_{u_{i}} \) is the set of RBs allocated to user \( u_{i} \). The value for \( \gamma_{\text{max}} \) is taken from [21] based on a maximum modulation scheme of 64-QAM in the downlink.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>LINK TO SYSTEM MAPPING PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>Value</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>0.6</td>
</tr>
<tr>
<td>( \gamma_{\text{min}} ) [dB]</td>
<td>-10</td>
</tr>
<tr>
<td>( \gamma_{\text{max}} ) [dB]</td>
<td>19.5</td>
</tr>
<tr>
<td>( C_{\text{max}} ) [bps/Hz]</td>
<td>4.4</td>
</tr>
</tbody>
</table>

December 31, 2009

DRAFT

176
A. Channel Model

The channel gain, $G_{mn}^{uv}$, between a transmitter $v$ and a receiver $u$, observed at receive antenna $m$ on RB $n$ as defined in (1), is composed of distance dependent path loss, log-normal shadowing and channel variations due to frequency-selective fading:

$$G_{mn}^{uv} = |H_{mn}^{uv}|^2 10^{-rac{(d_{mn} + X_m)}{10}},$$  

(6)

where $H_{mn}^{uv}$ accounts for the channel transfer factor between transmitter $v$ and receiver $u$ observed at receive antenna $m$ at RB $n$, $L(d)$ is the distance-dependent path loss (in dB), and $X_m$ is the log-normal shadowing value (in dB) with standard deviation $\sigma$, as described in [22]. Channel variations of $H_{mn}^{uv}$ on different receive antennas are mutually independent, while the path loss $L(d)$ is identical for all receive antennas $m$ and RBs $n$. While the channel response generally exhibits time and frequency dispersions, channel fluctuations within a RB are neglected because the RB dimensions are significantly smaller than the coherence time and coherence frequency of the channel [23]. The delay profiles associated with applicable propagation scenarios of [22], [24] are used to generate the frequency-selective fading channel transfer factor $H_{mn}^{uv}$.

B. Path Loss Models

Three path loss models are used depending on the type of link, as prescribed in [25]. For a purely outdoor link, i.e., the link (useful or interfering) between an eNB and an outdoor macro UE, the path loss is calculated as

$$L_{[\text{dB}]} = 15.3 + 37.6 \log_{10}(R),$$  

(7)

where $R$ (in m) is the distance between the transmitter and the receiver.

When considering the useful/interfering link between an eNB and a macro UE situated indoors or the interfering link between a femto UE (which is always situated indoors) and an eNB, the path loss includes the wall penetration loss and is calculated as

$$L_{[\text{dB}]} = 15.3 + 37.6 \log_{10}(R) + L_W,$$  

(8)

where $L_W$ is the wall penetration loss (in dB).

Finally, when considering the useful/interfering link between a HeNB and a femto UE or the interfering link between a macro UE and a HeNB, the path loss is calculated as

$$L_{[\text{dB}]} = 127 + 30 \log_{10}(R/1000).$$  

(9)
This is a simplified model based on LTE-A evaluation methodology which avoids modelling any walls.

Log-normal shadowing is added to all links. Correlated shadowing maps are applied such that the correlation in the shadowing values of two points is dependent on the distance between them. Table II shows the shadowing standard deviation $\sigma$ and auto-correlation shadowing distances for the macro and femto-cells [25].

<table>
<thead>
<tr>
<th>Table II</th>
<th>SHADOWING PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Macro-cell</td>
</tr>
<tr>
<td>Standard Deviation, $\sigma$</td>
<td>8 dB</td>
</tr>
<tr>
<td>Auto-correlation distance</td>
<td>50 m</td>
</tr>
</tbody>
</table>

III. FEMTO-CELL RESOURCE PARTITIONING

A. Downlink Interference Scenario for Closed-Access

As the eNB transmit power typically exceeds the HeNB transmit power by several orders of magnitude, $P_{\text{eNB}} \ll P_{\text{HeNB}}$, in most cases, the interference seen by macro UE $u$ will be dominated by eNB interference. Only if a macro-cell receiver, UE $u$, is located in close proximity to a HeNB $i$, UE $u$ is exposed to high HeNB interference $G_{i}^{\text{eNB}}P_{i}$, $i \in \mathcal{F}_{\text{HeNB}}$. In case UE $u$ is located indoors, the situation is exacerbated by the poor channel gains $G_{i}^{\text{eNB}}$, to the serving eNB $v_{\text{eNB}}$ caused by high wall penetration losses. This UE $u$ is likely to experience poor SINR (3). With full frequency reuse, femto-cells utilise all $N$ RBs. Therefore, the received SINR is likely to be unacceptable over the entire set of RBs allocated to UE $u$, i.e., $N_{\text{RB}}$.

B. Avoiding Femto-to-Macro Interference

Suppose that macro UE $u$ is located indoors within coverage of HeNB $i$, but served by an outdoor eNB $v_{\text{eNB}}$. An effective means of mitigating the destructive HeNB interference observed by UE $u$ is to introduce the concept of resource partitioning, such that HeNB $i$ is denied access to RBs, $N_{\text{RB}}$, that are assigned to UE $u$. In other words, the set of RBs allocated to UE $u$ must be left idle by HeNB $i$. Doing so completely eliminates the interference originating from the interfering HeNB $i$, which, in this case, is the most dominant source of interference. This increases the SINR (3) achieved at the macro UE.
In order to implement femto-cell resource partitioning, a pre-defined interference threshold, $I_{th}$, is introduced. Each macro UE measures the average channel gains $G_{mn}^{uv} = E\{G_{mn}^{uv}\}$ of nearby HeNBs and performs the following threshold test

$$10 \log E\{G_{mn}^{uv}\} = -L_{mn}^{uv}(d) + X_{\sigma} \geq I_{th} - P_L = G_{th}, \quad (10)$$

In case the average channel gain between a HeNB and the vulnerable macro UEs exceeds $G_{th}$, the HeNB is instructed to perform resource partitioning by suppressing transmission on RBs that are reserved by the vulnerable macro UEs. Clearly, decreasing the value of $I_{th}$ while keeping $P_L$ fixed increases the size of the “exclusion region” and protects a larger number of macro UEs, as seen in Fig. 2. Therefore, the lower the threshold $I_{th}$, the more resources are partitioned by HeNBs, so that the impact of resource partitioning on femto-cell performance increases as $I_{th}$ decreases.

It is possible that more than one macro UE experiences heavy interference from more than one HeNB. Suppose that HeNB $i$ causes strong interference to several UEs, as determined by the threshold test (10). Let the set of macro UEs exposed to strong interference from HeNB $i$ be denoted by $\mathcal{U}_d^i$. The associated
Fig. 2. Resource partitioning with two different thresholds ($G_{ih} > G_{ih}^d$). Using a lower threshold $b$ leads to a larger number of partitioned resources.

measurement and signalling procedures on how each UE in $\mathcal{U}_{\text{diff}}^i$ identifies the interfering HeNB $i$ are detailed in Sections III-C. As per the resource partitioning concept, HeNB $i$ must partition resources such that it does not cause interference to the set of macro UEs $\mathcal{U}_{\text{diff}}$. In other words, the resources that are prohibited for HeNB $i$ are in the form

$$\overline{\mathcal{N}}_{i} = \bigcup_{u \in \mathcal{U}_{\text{diff}}} \mathcal{N}_{u}. \quad (11)$$

We note that the affected macro UEs within $\mathcal{U}_{\text{diff}}^i$ may be connected to different macro eNBs, as HeNB $i$ may be within the coverage area of several macro-cells.

In general, every HeNB that causes high interference to nearby macro UEs must partition resources as explained by (11). However, due to the low HeNB transmit power, $P_1$, it is unlikely that many macro UEs experience heavy interference from the same femto-cell. Hence, only a small subset of the users served by an eNB are interfered by the same set of HeNBs as illustrated in Fig. 1. This implies that the number of RBs $\overline{\mathcal{N}}_{i}| = \overline{\mathcal{N}}_{i}$ that must not be used by an interfering HeNB is much smaller than the total number of RBs, $\overline{\mathcal{N}}_{i} \ll \mathcal{N}$, so that the degradation of femto-cell capacity is expected to be modest.

C. Practical Implementation in LTE Systems

In order to implement the resource partitioning concept, the interfering femto-cell needs to be identified and then be informed of the restricted resources $\overline{\mathcal{N}}_{i}$ it must not use according to (11). This involves
integrating the proposed resource partitioning concept within the network architecture. In abstract, femto-cell resource partitioning is integrated to the LTE network architecture by the following procedure:

1) Macro UE \( u \) determines the cell-ID of surrounding HeNBs, by reading the corresponding broadcast channel (BCH), and stores them in a list containing neighboring cell-IDs.

2) UE \( u \) identifies the heavily interfering HeNBs in its proximity using reference signal received power (RSRP) measurements.

3) The cell-IDs of the corresponding HeNBs are reported to the serving eNB.

4) The eNB prepares a DL-HII bitmap containing information about which RBs are transmitted with high power.

5) The DL-HII bitmap is disseminated to neighboring HeNBs over the X2 or S1 interfaces.

6) If the receiving eNB is a HeNB, it will refrain from using the particular RBs marked in the DL-HII bitmap. In this way, detrimental downlink femto-cell interference at the vulnerable macro UEs is avoided.

The necessary UE measurements that identify which femto-cells are in close vicinity of a macro UE are similar to a handover procedure. In LTE, macro UEs read the broadcast channel (BCH) not only from their primary eNB, but also from one or several secondary eNBs. As the BCH contains the cell-IDs, a UE can establish a list of neighbouring eNBs. Knowledge of the cell-ID also enables UEs to read the cell-specific reference signals (also known as training symbols or pilots) of neighboring eNBs, which are needed to carry out RSRP measurements to estimate the average channel gain between the UE and the surrounding eNBs, \( C_{\text{b},u} \), in (10). RSRP for a specific cell is defined as the linear average over the power contributions (in W) of the Resource Elements (REs) which carry cell-specific reference signals within the considered measurement frequency bandwidth [12]. As HeNBs also broadcast their cell-ID in the BCH, as well as cell-specific reference signals, RSRP measurements allow the identification of HeNBs that are in close proximity of a macro UE. We note that this does not introduce any additional overhead, since we utilize an existing signalling procedure between macro UEs and eNBs.

The eNB needs to inform the HeNB that causes interference of the restricted resources, \( \mathcal{N}_h \), it must not use according to (11). This involves the transport of control information from eNBs to HeNBs using the LTE network architecture shown in Fig. 3. The S1 interface connects the Serving Gateway (S-GW)/Mobility Management Entity (MME) with a pool of neighboring eNBs. The MME is a control node which processes the signalling between the UE and the core network (CN). Neighbouring eNBs are interconnected via the X2 interface, which conveys control information related to handover.
and interference coordination. The X2 interface is therefore particularly suited for signalling related to femto-to-macro interference avoidance [17], [18].

Fig. 3. Overall LTE architecture showing S1 and X2 interfaces.

In LTE, the network architecture is flat such that when a UE is handed over, in order to improve latency and efficiency, the handover procedure is exclusively controlled by the source and destination eNBs [26]. For intra-LTE handover, the default procedure is that the source eNB buffers the data and passes it to the destination eNB over the X2 interface. If no X2 interface exists between the source and destination eNBs, the handover is performed over the S1 interface. However, from the UE's viewpoint, there is no difference between the two types of handover [26]. In the case of closed-access femto-cells, where a handover is not possible between a source H/eNB and a destination H/eNB, the proposed resource partitioning procedure requires that signalling information is conveyed from the source eNB to the destination H/eNB.

In the LTE downlink, a bitmap known as the Relative Narrowband Transmit Power (RNTP) indicator is exchanged over the X2 interface between eNBs. The RNTP indicator is used by an eNB to signal to neighbouring eNBs on which RBs it intends to transmit with high power in the near future. Each bit of the RNTP indicator corresponds to one RB in the frequency domain and is used to inform the neighbouring eNBs if the eNB in question is planning to exceed the transmit power for that RB or not [27]. The value of the threshold and the time period for which the indicator is valid are configurable parameters. This
bitmap is intended to enable neighbouring cells to estimate the amount of interference on each RB in future frames and therefore schedule their UEs accordingly. Furthermore, the source and destination cell IDs need is contained in the RNTP.

The DL-HIII messages that indicate which resources a particular HeNB must not use may be conveyed by a bitmap that is equivalent to that of the RNTP indicator. Provided that HeNBs are also connected to the X2 interface, DL-HIII messages emitted by eNBs may be configured to perform resource partitioning at certain HeNBs by using the format of the RNTP indicator. Suppose that macro UE $u$ served by eNB $v$, is trapped within the coverage area of a closed-access femto-cell served by HeNB $i$. Then resource partitioning is implemented by sending a DL-HIII message to HeNB $i$, where ones and zeros correspond to RBs where HeNB $i$ may and may not transmit, respectively. The transmission format of the RNTP indicator is therefore perfectly suited for DL-HIII messages.

In order to avoid that DL-HIII messages are to be sent every subframe (i.e., at 1 ms intervals), the lifetime of DL-HIII messages could be configured in a dedicated field within the DL-HIII message format. Dependent on the underlying service the macro UE is using, the eNB estimates for how long the RBs utilized macro UE are to be reserved, and notes this estimate as the lifetime of the DL-HIII message. Unless DL-HIII message is updated before its lifetime expires, the HeNB may then reuse the restricted RBs after the lifetime of the DL-HIII message has expired. This limits the signalling overhead due to DL-HIII messages to a level comparable to that of a handover procedure, which is needed, e.g., for macro-to-femto-cell handover in open access systems.

Historical UE information is propagated between eNBs during the X2 handover procedure [26]. Historical UE information consists of the last few cells visited by the UE, together with the time for which the UE was camped at that eNB. The historical information is used to determine the occurrence of a handover ping-pong between cells. This is also a source of information that is useful in the context of resource partitioning. If a UE is camped to the last few eNBs for a short time interval, the resource partitioning procedure need not be carried out. This can be done in order to avoid unnecessary signalling.

IV. SYSTEM LEVEL SIMULATION SETUP

A. User Distribution and Sectorized eNBs

The simulation area comprises a two-tier, tessellated hexagonal cell distribution. In order to eliminate edge effects with regards to interference, an additional two tiers are simulated. However statistics are taken only from the first two tiers. The eNBs are placed at the junction of three hexagonal cells, such that each cell can be considered as a sector. In this way, each eNB serves three sectors, with each sector
reusing all frequency resources. For each sector, the azimuth antenna pattern, $A(\theta)$, is described by [25]

$$A(\theta) = -\min \left[ 12 \left( \frac{\theta}{\theta_{3dB}} \right)^2, A_m \right],$$

(12)

where the $\theta_{3dB}=70^\circ$ is the angle from the central lobe at which the gain reduces to half the maximum value and $A_m=20$ dB is the maximum possible attenuation due to sectorization.

We follow the simulation assumptions described in [25] where a 5x5 grid model is used to simulate femto-cell deployment. This setup models a single-floor building with 25 apartments that are arranged in a 5x5 grid. A HeNB may exist in an apartment with probability $p_1$. Furthermore, a HeNB may be active with probability $p_2$. Therefore, the probability $p$ that an apartment contains an active HeNB is given by $p = p_1 p_2$. Every apartment that contains an active HeNB contains exactly one associated femto UE. These are dropped randomly and uniformly within the apartment with a specified minimum separation from the HeNB. In addition to this, macro UEs are also randomly and uniformly dropped within the tiered hexagonal system. As a result, it is possible that a macro UE lies within the confines of an apartment. Fig. 4 shows one instance of a distribution of four apartment blocks and ten macro UEs per macro sector.

It is observed that some macro UEs lie within apartment blocks. We assume a closed-access policy so that such macro UEs, despite their indoor location, are served by the eNB. In such a situation, these macro UEs suffer from severe interference originating from the nearby HeNBs. Macro UEs lying either inside an apartment block containing active HeNBs or very close to such an apartment block are the likely victims of high downlink femto-to-macro interference. The concept of resource partitioning addresses the mitigation of interference experienced by such macro UEs in the downlink. The macro UEs indicated by arrows in Fig. 4 are the potential recipients of high interference originating from nearby femto-cells.

In this particular case, if one or more HeNBs are indeed the cause of high interference, they will partition resources so as to enable the vulnerable macro UEs to attain a satisfactory downlink SINR.

\textbf{B. Time Evolution}

Since the resource allocation is random in nature, each run of the Monte Carlo simulation is iterated over a series of snapshots in order to obtain statistically accurate results. The duration of a snapshot is equivalent to the duration of one LTE subframe and the run is allowed to iterate over ten subframes (one LTE frame). The time duration of the subframe, $t_{\text{sub}}$, is listed in Table III. At each iteration, the allocation of resources is randomised. It is assumed that the UEs are quasi-static for the duration of the run.
Fig. 4. Four apartment blocks and ten macro UEs per macro sector. Macro UEs are denoted by red dots, femto UEs by blue diamonds, HeNBs by green crosses and eNBs by filled green circles, each denoted with a number. The close-up shows a few marked macro UEs undergoing potentially severe downlink interference from nearby active femtocells.

V. RESULTS

The simulation is run for a full-buffer traffic model, which resembles the worst case scenario where all users in the system are active simultaneously. Furthermore, the users in the system are assumed to be static for the duration of the snapshot, so that the effects due to Doppler spread are neglected. Perfect synchronisation in time and frequency is assumed, such that interference between neighboring RBs can be neglected as well. Relevant parameters used for the simulation are shown in Table III.

Clearly, more than one macro UE can be affected by the same apartment block and more than one apartment block can affect the same macro UE (as demonstrated in Fig. 4). The offending HeNBs must then perform resource partitioning using the method described in Sections III-B and III-C. Due to the effects of shadowing, the corresponding exclusion region is not a circular area.

For a meaningful performance assessment, the definition of “affected” macro and femto UEs is to be introduced. A macro UE is said to be “affected” if its average channel gain to at least one HeNB exceeds the pre-defined threshold $I_{th}$, as defined in (10). This section shows results for different classes of UEs: overall macro (all macro UEs in the system, regardless of their location), overall femto (all femto UEs, all
TABLE III
SIMULATION PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. 5×5 apartment blocks per macro-cell sector</td>
<td>{4, 14}</td>
</tr>
<tr>
<td>Avg. macro UEs per macro-cell sector</td>
<td>10</td>
</tr>
<tr>
<td>Intersite distance</td>
<td>500 m</td>
</tr>
<tr>
<td>Individual apartment dimensions</td>
<td>10×10m²</td>
</tr>
<tr>
<td>HeNB deployment probability, p₁</td>
<td>0.2</td>
</tr>
<tr>
<td>HeNB activation probability, p₂</td>
<td>0.5</td>
</tr>
<tr>
<td>Femto UEs per active femto-cell</td>
<td>1</td>
</tr>
<tr>
<td>Downlink FDD band</td>
<td>[2.60, 2.63] GHz</td>
</tr>
<tr>
<td>Tot. number of available RBs, N</td>
<td>50</td>
</tr>
<tr>
<td>RB bandwidth, BR</td>
<td>1800 kHz</td>
</tr>
<tr>
<td>Thermal noise, η</td>
<td>-174 dBm/Hz</td>
</tr>
<tr>
<td>eNB transmit power per RB per sector, Pₑₑ</td>
<td>29 dBm</td>
</tr>
<tr>
<td>HeNB transmit power per RB, Pₑₑ</td>
<td>3 dBm</td>
</tr>
<tr>
<td>eNB antenna gain</td>
<td>14 dBi</td>
</tr>
<tr>
<td>Sectors per eNB</td>
<td>3</td>
</tr>
<tr>
<td>Min. distance between macro UE and eNB</td>
<td>35 m</td>
</tr>
<tr>
<td>Min. distance between femto UE and HeNB</td>
<td>0.2 m</td>
</tr>
<tr>
<td>Number of macro/femto Rx antennas</td>
<td>2 Rx</td>
</tr>
<tr>
<td>Wall penetration loss, Lₑₑ</td>
<td>20 dB</td>
</tr>
<tr>
<td>Interference threshold, (I₀)</td>
<td>{(-72, -87) dBm}</td>
</tr>
<tr>
<td>Subframe time duration, (tₙ)</td>
<td>1 ms</td>
</tr>
</tbody>
</table>

lying strictly indoors associated with an active HeNB), affected macro (only macro UEs in the vicinity of active femto-cells as described above) and affected femto (only femto UEs served by offending HeNBs).

Fig. 5 demonstrates the need for femto-to-macro interference coordination and the benefit of resource partitioning. The cumulative distribution function (CDF) of downlink interference only for affected macro UEs for a system consisting of four apartment blocks and ten macro UEs per macro-cell sector with and
without resource partitioning. An interference threshold of \( I_{th} = -72 \text{dBm}, \) \( i.e., \) \( G_{th} = -75 \text{ dB} \) is used. For comparison purposes, a third CDF is displayed showing the interference only from the macro layer, \( i.e., \) HeNB transmit powers are reduced to zero, keeping the allocation of resources unchanged. This third case represents the “ideal” situation where there is no interference from the femto layer since priority is assumed to lie with macro UEs. The performance of any scheme to mitigate downlink interference for affected macro UEs must approach the performance of this “ideal” case. It is clear from the figure that resource partitioning reduces the interference by approximately 10 dB at the 50th percentile. Furthermore, it is seen that resource partitioning approaches the performance of the benchmark particularly in the high interference regime, where the offending HeNBs suppress transmission on the vulnerable RBs. The difference between the lower interference regimes of the curve with resource partitioning and the case without femto interference indicates the amount of additional interference caused by HeNBs that do not perform resource partitioning because they do not lie in the vicinity of any vulnerable macro UEs. Therefore, it is clear from this figure that there is a significant benefit to be made from resource partitioning. The following figures show the effect of resource partitioning on the macro and femto performance.

The capacity performances of combined macro and femto-cell depicted in Figs. 6 through 9 are compared against a benchmark system that emulates a state-of-the-art cellular network. In this benchmark system no HeNBs exist, \( i.e., \) all UEs previously classified as femto UEs are served by the outdoor eNBs. All UEs in the benchmark system are therefore macro UEs and must share the available macro resources.

Fig. 6 shows the overall downlink macro user capacity for 4 and 14 grids with 10 macro UEs per macro-cell sector and for \( I_{th} = -72 \) and \( -87 \text{ dBm} \). The two \( I_{th} \) values are chosen in particular because they represent two extreme cases: one in which the exclusion region is small enough to cause approximately 13% of HeNBs to partition resources (\( I_{th} = -72 \text{ dBm} \)) and the other (\( -87 \text{ dBm} \)) where the exclusion region is large enough to cause approximately 76% of HeNBs to partition resources. In this case, capacity statistics are collected from all macro UEs, regardless of whether they lie outdoors or indoors and regardless of whether they are vulnerable to heavy HeNB interference or not. It is observed that when resource partitioning is applied, a consistent gain is achieved over the case where no resource partitioning is used, \( i.e., \) both macro and femto-cells fully utilise all available resources.

Fig. 6 reveals that there is a higher resource partitioning gain in the lower capacity regime (lower percentiles of the CDF). This is due to affected macro UEs that severely suffer from interference originating from nearby HeNBs. In the higher capacity regime, resource partitioning gains diminish, since macro UEs achieving high capacities typically lie outdoors, well protected from interfering HeNBs.
Fig. 5. CDFs showing downlink interference for affected macro UEs in systems with and without resource partitioning, compared against a system with no femto interference.

Through walls, so that the dominant interference for such macro UEs originates from other eNBs.

It is observed that the performance of the system with 14 grids per macro-cell sector shown in Fig. 6(b) is consistently worse than the performance of the system with lower grid density shown in Fig. 6(a). This is expected as increasing the grid density increases the amount of interference originating from the femto layer. For the benchmark, a higher grid density means that the same amount of resources in the macro-cell have to be shared among a higher number of users, thus compromising user capacity. Interestingly, it is observed that when $I_{th} = -87$ dBm, the performance of the systems with either grid density are almost identical. This is attributed to the fact that in either case, the number of macro UEs remains the same, and the high value of $I_{th}$ then ensures that the majority of HeNBs partition resources. As a result, the amount of femto interference stays largely independent of the grid density. Of note is the fact that a decreasing $I_{th}$ enhances the attainable gains in macro UE capacity.

It is clear from Fig. 6 that augmenting a cellular network with femto-cell deployment yields tremendous capacity gains over the benchmark system. These gains are attributed to two reasons. First, in the
benchmark system, all former femto UEs are served by the outdoor eNB, where high wall penetration losses result in a highly attenuated signal. The second reason is that in the benchmark system, all UEs must share the macro resources, so that each UE is assigned fewer RBs compared to the case with femto-cell deployment. For four apartment blocks per sector (Fig. 6(a)), with each apartment having a 10% probability of containing an active HeNB, each sector contains, on average, ten femto UEs in addition to the ten macro UEs. This means that in the benchmark system, each macro UE is allocated half the number of RBs in comparison to the system with femto-cell deployment. Therefore, in the benchmark system, the spatial reuse gain that is made available through femto-cell deployment is lost. The situation is obviously worsened in the 14 grid per sector case, as shown in Fig. 6(b). This is also responsible for the benchmark system showing the highest outage. In this context, a UE goes into outage if the achieved SINR on all RBs is less than $\gamma_{\text{min}}$.

Finally, in the very low capacity regime ($< 0.1$ Mbps in either case), the benchmark system outperforms the system without resource partitioning. This is due to excessive femto-to-macro interference experienced by macro UEs trapped within the coverage area of femto-cells.

Fig. 7 shows the overall femto user capacity on the downlink. Results are gathered for all femto UEs, regardless on whether they are in the vicinity of a vulnerable macro UE. In general, very high capacities are achieved in femto-cells. This is due to the very short transmission distances within femto-cells and outdoor interference protection through high wall penetration losses. We observe that in all cases, user
capacities saturate at 39.6 Mbps due to the upper bound of the link-to-system mapping (4). According to (4) the maximum achievable spectral efficiency is capped at $C_{max} = 4.4 \text{ bit/s/Hz}$ and since HeNBs only serve one femto UE, with all available resources $N$ being allocated to this UE, this equates to a maximum downlink capacity of 39.6 Mbps.

Fig. 7 also reveals that femto-cells must sacrifice some capacity when resource partitioning is in place. This is obvious since the affected HeNBs are forbidden from using RBs allocated to nearby macro UEs. Moreover, the lower the threshold $I_{th}$, the higher the partitioning of femto-cell resources, and thus the lower the proportion of femto UEs that approach the maximum capacity. For $I_{th} = -72 \text{ dBm}$, the degradation in femto user capacity is in the order of 1 Mbps. On the other hand, when $I_{th} = -87 \text{ dBm}$, the degradation increases to approximately 10 Mbps. It is important to note that owing to the full buffer assumption, the degradation in femto user capacities reflects a worst case scenario. In case femto-cells do not utilize all available resources, the degradation due to resource partitioning is obviously lower.

A trade-off between the improvement in macro capacity and degradation of femto capacity exists.
Optimization of this trade-off depends on the acceptable degradation of macro-cell capacity (see Fig. 6), in particular at the low percentiles of the corresponding CDF. This enables the determination of the appropriate threshold $I_{th}$, which in turn results in a certain degradation of femto-cell performance.

Figs. 8 and 9 concentrate on affected macro and femto UEs. Fig. 8 shows the capacity performance of affected macro UEs. It is observed that resource partitioning delivers a significant gain to the downlink performance of affected macro UEs. It is seen that regardless of the grid density, with $I_{th} = -72$ and $-87$ dBm, a five and, respectively, ten-fold capacity increase of affected macro UEs is observed.

Fig. 9 shows the sacrifice in downlink capacity that affected femto UEs must incur in order to enable resource partitioning. It is observed that UEs associated with HoNBs that must partition resources incur a reduction in capacity of approximately 25% with $I_{th} = -72$ dBm and 39% with $I_{th} = -87$ dBm. It is important to note that for a sacrifice of 39% of femto capacity, the affected macro UEs are rewarded with a significant ten-fold capacity increase. We note that with either grid density, the affected macro and femto UE performance is almost identical because in both cases, the macro UE density remains the same and therefore, every HeNB must partition the same proportion of resources.

![CDF Diagram](image)

**Fig. 8.** CDFs showing downlink user capacity only for affected macro UEs for a system with resource partitioning compared against a system without resource partitioning.
Fig. 9. CDFs showing downlink user capacity only for affected femto UEs for a system with resource partitioning compared against a system without resource partitioning.

The sum system capacity in the downlink normalised per macro sector shows some interesting trends. With a grid density of 4 grids per macro-cell sector and $I_{th} = -72$ dBm, the use of resource partitioning results in an affected macro UE capacity increase of 6.4% at the cost of a 2.8% degradation in femto capacity. However, when $I_{th} = -87$ dBm, a 14.2% increase in macro capacity is accompanied by a 29.6% decrease in femto capacity. The situation is different for the case when the grid density is increased to 14 grids per macro sector. When $I_{th} = -72$ dBm, a 15.7% increase in macro capacity is attained at the expense of a 2.8% decrease in femto capacity. For $I_{th} = -87$ dBm, resource partitioning results in a 53.2% increase in affected macro UE capacity with a 25.1% decrease in femto capacity. This shows that with decreasing grid densities, a relatively high interference threshold $I_{th}$ becomes more effective.

VI. SUMMARY AND CONCLUSION

Femto-cell deployment poses a viable complement to cellular networks. Operators need to bear low cost in their deployment, since they are installed directly by the users themselves. Furthermore, since they share both the radio access scheme and the frequency band with eNBs, they are compatible with
legacy UEs. Aside from these benefits, a cellular network stands to significantly gain in overall system throughput through the widespread deployment of HeNBs. Not only do HeNBs improve indoor coverage, bringing broadband-like experience directly to the handset, but they also offload resources from the eNB which can be utilised to improve coverage to outdoor users.

It has been seen that in a closed-access system, macro UEs lying in the proximity of femto-cells experience at least as much downlink interference from HeNBs as they do from eNBs. It has been demonstrated that by introducing resource partitioning, the capacity of such macro UEs can be boosted by a factor of ten. The cost incurred by femto UEs in doing so is minimal as they lose less than half of their capacity (which is more than one order of magnitude higher than macro UE downlink capacity). Users therefore experience a very high throughput inside femto-cells due to the favourable channel conditions and continue to do so even in the presence of resource partitioning. Introducing resource partitioning to a closed-access system with femto-cell deployment substantially boosts the sum system capacity while ensuring reliable macro-cell operation.

ACKNOWLEDGEMENT

Initial parts of this work were supported by DFG grant HA 3570/2-1 as part of program SPP-1163 (adaptability in heterogeneous communication networks with wireless access – AKOM) while some latter parts of this work have been performed within the framework of the CELTIC project CP5-026 WINNER+. Harald Haas acknowledges the Scottish Funding Council support of his position within the Edinburgh Research Partnership in Engineering and Mathematics between the University of Edinburgh and Heriot Watt University.
REFERENCES


References


