Radio Resource Management and Transmission Modes for Two-Tier Cellular Systems

by

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A thesis submitted in conformity with the requirements for the degree of Master of Applied Science
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University of Toronto

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Abstract

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This thesis explores the paradigm of two-tier connectivity, in which secondary nodes utilizing wireless backhauling facilitate the connectivity of system users to base stations in a macro cellular communication setup. When compared to smaller cells utilizing wired backhauling to offload user traffic from macro base stations in conventional heterogeneous network approaches, secondary nodes of two-tier systems offer increased placement flexibility to connect user clusters, which is shown to be instrumental for maximizing densification gains and improving the performance of cell edge users. Depending on user distribution, utilized frequency bands and the capabilities of secondary nodes, up to 179% gains in the average and cell edge throughput rates are observed when augmenting macro cellular communication systems with secondary nodes.
Dedication

I dedicate this thesis to my family, for their endless love and support.
Acknowledgements

I would first like to thank my supervisor Professor Elvino Sousa of the Department of Electrical and Computer Engineering at University of Toronto. Professor Sousa provided excellent opportunities to learn and grow.

I would also like to thank Dr Ahmed Alsohaily for his deep insight and advice on my research and my writing.
# Contents

Dedication ................................................. iii  
Acknowledgements ................................. iv  
Contents .............................................. v  
List of Figures .............................. vii  

1 Introduction ................................. 1  
1.1 Heterogeneous and Overlaid Networks ................. 2  
1.2 MIMO Techniques .................................... 4  
1.3 Two-Tier Cellular Communication Systems ............. 7  
1.4 Thesis Contribution and Outline ...................... 9  

2 System Model ................................. 10  
2.1 System Layout and Frequency Bands .................. 10  
2.2 User Distribution and Mobility ....................... 13  
2.3 Simulation Structuring ............................ 16  
2.4 Propagation Environment ......................... 18  
2.5 Channel Model ..................................... 19  
2.6 Channel Matrix Calculation ......................... 22  
2.7 Throughput Calculation ............................. 24  
2.8 Resource Allocation ................................. 25  
2.9 Proportional Fair Scheduling ......................... 25
3 Modelling and Design Considerations for Two-Tier Cellular Communication Systems

3.1 Clustering Users at the S-nodes ................................................. 28
3.2 Dispersion Index - Clustering Criteria ........................................ 30
3.3 Modified System Simulation for Two-Tier Evaluation .................... 32

4 Simulation Results

4.1 Baseline Performance .............................................................. 36
4.2 Two-Tier Performance ............................................................ 38

5 Conclusions and Future Work

5.1 Conclusions .............................................................................. 53
5.2 Future Work ........................................................................... 54
# List of Figures

1.1 Heterogeneous networks overlay macrocells with small cells .......................... 3
1.2 An example of overlaid frequency deployment with four coverage layers .... 3
1.3 Large antenna arrays at a macrocell tower .................................................. 6
1.4 Enhanced channel serving as S-node’s wireless backhaul ............................. 7
1.5 Users connecting on second tier leverage higher capacity ......................... 8

2.1 Hexagonal grid representation of a single-tier macro cell network with users uniformly distributed ................................................................. 11
2.2 Distances using wraparound method .............................................................. 11
2.3 Antenna gain pattern for a base station transmission sector. 3GPP 25.996 [11] .................................. .............................................. 13
2.4 Antenna gain pattern for a base station utilizing three sectors. 3GPP 25.996 [11] .................................. .............................................. 14
2.5 Randomized user mobility modeled in simulations ........................................ 15
2.6 Number of users in any region $B \subset \mathbb{R}^2$ follows a Poisson distribution ... 16
2.7 Uniform distribution of users in a regular cell .............................................. 17
2.8 Uniform distribution of users subsequently clustered at hot spots ............... 17
2.9 Channel modeling ......................................................................................... 20
2.10 3GPP 25.996, showing various physical parameters for link level channel model used in system simulations. [11] .................................. .............................................. 21
## 2.11 3GPP 25.996, showing various physical parameters for link level channel model used in system simulations. [11] .......................... 22

## 2.12 LTE resource block, 0.5 ms by 180 KHz .......................... 26

## 2.13 LTE resource grid [12] .............................................. 27

## 3.1 Clustering with contraction parameter of 1 (uniform) ................. 34

## 3.2 Clustering with contraction parameter of 5 .......................... 34

## 3.3 Clustering with contraction parameter of 10 .......................... 34

## 3.4 Clustering with contraction parameter of 15 .......................... 34

## 3.5 Clustering with contraction parameter of 20 .......................... 34

## 4.1 Baseline system performance: Single tier rural deployment at 800 MHz .......................... 38

## 4.2 Baseline system performance: Single tier rural deployment at 2600 MHz .......................... 39

## 4.3 Baseline system performance: Single tier rural deployment at 3500 MHz .......................... 40

## 4.4 Baseline system performance: Single tier suburban deployment at 800 MHz .......................... 41

## 4.5 Baseline system performance: Single tier suburban deployment at 2600 MHz .......................... 42

## 4.6 Baseline system performance: Single tier suburban deployment at 3500 MHz .......................... 43

## 4.7 Baseline system performance: Single tier urban deployment at 800 MHz .......................... 44

## 4.8 Baseline system performance: Single tier urban deployment at 2600 MHz .......................... 45

## 4.9 Baseline system performance: Single tier urban deployment at 3500 MHz .......................... 46

## 4.10 Baseline system performance: Single tier dense urban deployment at 800 MHz .......................... 47

## 4.11 Baseline system performance: Single tier dense urban deployment at 2600 MHz .......................... 48

## 4.12 Baseline system performance: Single tier dense urban deployment at 3500 MHz .......................... 49

## 4.13 Suburban coverage 88% using 2.6 GHz .......................... 51

## 4.14 Rural coverage 72% using 2.6 GHz .......................... 51
4.15 Suburban coverage 99% using 2.6 GHz with Two-Tier . . . . . . . . . . . . . 51
4.16 Rural coverage 89% using 2.6 GHz with Two-Tier . . . . . . . . . . . . . 51
4.17 Suburban coverage 100% using 2.6 GHz with Two-Tier for clustered users 51
4.18 Rural coverage 98% using 2.6 GHz with Two-Tier for clustered users . . 51
4.19 Suburban coverage 73% using 3.5 GHz . . . . . . . . . . . . . . . . . . . 52
4.20 Rural coverage 52% using 3.5 GHz . . . . . . . . . . . . . . . . . . . . . 52
4.21 Suburban coverage 80% using 3.5 GHz with Two-Tier . . . . . . . . . . . 52
4.22 Rural coverage 66% using 3.5 GHz with Two-Tier . . . . . . . . . . . . . 52
4.23 Suburban coverage 93% using 3.5 GHz with Two-Tier for clustered users 52
4.24 Rural coverage 78% using 3.5 GHz with Two-Tier for clustered users . . 52

5.1 Heterogeneous network including S-nodes . . . . . . . . . . . . . . . . . . 54
Chapter 1

Introduction

The ongoing efforts to improve the coverage, capacity and throughput rates of cellular communication systems have led to the development and introduction of a wide range of enhancements covering every aspect of these systems. Starting from the early AMPS systems, which was subsequently denoted as the first generation of cellular systems (1G), cellular radio access networks, core networks and radio interfaces have undergone rapid improvements that have paved the way for current advances in 4G and 5G systems.

Fundamentally, a look at the Shannon-Hartley formula [1]

\[
C = B \log_2 (1 + \frac{S}{I+N})
\]  

(1.1)

shows that, when fixing all other parameters, increasing the capacity of wireless channels, and subsequently the capacity of cellular communication systems, entails increasing the Signal to Interference plus Noise (SINR) ratio \((\frac{S}{I+N})\) and/or the transmission bandwidth. Nevertheless, the limited availability of radio frequency resources shifts the focus to improving the SINR, which cannot be improved by simply increasing transmission power due to the interference-limited nature of cellular systems. Since frequency reuse is the fundamental foundation of wireless cellular communications, increasing transmission
power levels at system cells would increase the interference levels throughout the system and negatively impact the system capacity [4]. Ultimately, the design of cellular systems can be viewed as a balancing act between the various system performance requirements on the one hand versus the cost and complexity constraints and limitations on the other hand.

## 1.1 Heterogeneous and Overlaid Networks

The term network densification refers to the increase of number of cells within a given geographic area. Network densification constitutes one of the most effective solutions for improving the capacity of cellular communication systems deployed in user-dense areas [6]. If this solution is employed to improve capacity in a cellular system, the size of large macro cells would ideally be reduced proportional to the current and forecasted user density and traffic demand. Doing so should increase the density of system cells per unit area. Nevertheless, the prohibitive costs of network densification resulted in the adoption of a hybrid heterogeneous network deployment model, shown in Figure 1.1, in which macro base stations are complimented by various classes of base stations such as microcell, picocell, femtocell, to accommodate and adapt to user distribution and traffic demand. Even without the deployment of small cells, contemporary cellular communication systems naturally converge to overlaid coverage layers due to the utilization of multiple frequency bands at legacy macro base station sites typically positioned based on lower frequency bands as shown in Figure 1.2.

Ideally in cellular systems utilizing small cells, smaller cells would be strategically placed in areas generating high traffic demand to relieve traffic congestion at macro cells. Furthermore, due to the smaller form factor and lower power requirements, small cells provide higher placement flexibility to adapt to changing traffic requirements and ex-
Figure 1.1: Heterogeneous networks overlay macrocells with small cells

Figure 1.2: An example of overlaid frequency deployment with four coverage layers

pand the network capacity in an organic manner when compared to macro base stations. Nevertheless, small cells require reliable backhaul connections to meet the network access latency and throughput rate requirements entailed by the target Quality of Service (QoS) levels, which substantially constrains the placement of small cells. Additionally, care must be taken when designing small cell access to avoid interfering with the operation of macro cells. In many cases this objective is achieved by using orthogonal transmissions in frequency, i.e. by using different frequency bands for smaller cells operating within the coverage range of a macro cell, including the use of unlicensed frequency
bands via Wi-Fi traffic offloading. Subsequently, interference management forms another key design challenge for heterogeneous cellular communication systems.

1.2 MIMO Techniques

Multiantenna transmission is another solution to improve capacity in a wireless communication network. Increasing the number of antennas at the transmitter and/or receiver sides in a wireless communication system will provide gains in the form of added diversity to alleviate the limitations introduced by channel fading. When each antenna is simply transmitting the same message, the collective transmissions can be combined constructively to improve the SINR and, subsequently, the channel capacity. This is referred to as beamforming.

The theoretical channel capacity in a multiple input multiple output (MIMO) wireless channel can be further increased by up to a factor equal to the maximal number of utilized antenna elements at the transmitter or receiver sides by exploiting the spatial dimensions of the transmitted and received signals; as the singular-value decomposition of a MIMO communication channel yields a gain proportional to the spatial diversity of the channel components. Specifically, the channel matrix $H$ can be described in its singular value decomposition to showcase the equivalent parallel Gaussian channels derived for spatially multiplexed MIMO communications. [5]

$$H = U\Lambda V^*$$ (1.2)

Where $U$ and $V$ are unitary rotational matrices. The matrix $\Lambda$ is a diagonal matrix with diagonal elements $\lambda_i$. The number of non-zero diagonal elements is the rank of the MIMO channel and specifies the number of parallel streams that can be simultaneously
Chapter 1. Introduction

transmitted. Showing $H$ as the sum of rank one matrices:

$$H = \sum_{i=1}^{\min n} \lambda_i u_i v_i^*$$  \hspace{1cm} (1.3)

where $u_i$ and $v_i$ are vectors. $u_i$ are the column components of matrix $U$, and $v_i$ are the row components of matrix $V$.

Therefore, with $n$ linearly independent streams in a MIMO channel, the channel capacity can be increased by up to $n$ times, calculated using the modified capacity formula:

$$C = E[\log(\det(I_n + \frac{\text{SNR}}{n_t} HH^*))]$$  \hspace{1cm} (1.4)

MIMO gains have been further advanced in the "Massive MIMO" and "Multi-user MIMO" paradigms, in which large MIMO arrays are utilized using a multitude of configurations to simultaneously connect multiple system users \[8\]. In both paradigms, the number of antenna elements employed at the base station, while not being rigidly defined or constrained, is in the order of tens or hundreds of elements. Such a large number of antenna elements far exceeds the number of antenna elements that can be placed in user equipment, simply due to the inherent power and area limitations of user equipment. In such cases capacity gains are primarily realized using beamforming and/or spatial multiplexing of user data streams when utilizing multi-user MIMO \[7\].
Figure 1.3: Large antenna arrays at a macrocell tower
1.3 Two-Tier Cellular Communication Systems

Considering the evolution of cellular networks, both in terms of architecture and service diversity, a fundamental bottleneck in radio access, inevitably introduced by the constraints imposed on the placement of system cells utilizing wired backhauling, led to the emergence of a new class of base stations utilizing wireless backhaul solutions to compliment wire-backhauled base stations in 5G systems [14]. Such base stations essentially act as highly efficient concentrators, or hot spots, carrying user equipment (UE) traffic through a strong wireless connection to a macro base station, as shown in Figure 1.3, and are referred to as "secondary nodes" or "S-nodes" in this thesis.

Unlike user equipment (UE) constrained by size, transmission power and energy limitations when connecting to base stations, S-nodes access radio access networks using substantially larger antenna arrays, higher transmission power, and far less design constraints to achieve superior utilization of radio frequency resources. As depicted in figure 1.4, UE in close proximity to S-nodes can then capitalize on the enhanced connectivity of S-nodes, with the overall effect being equivalent to bringing UE closer to the radio access network at the expense of a small increase in latency. Latency is not considered in this thesis as assumed applications are not severely sensitive to minor transmission delays.
S-nodes can also play a pivotal role in enabling one of the key use cases of 5G cellular systems - namely massive machine type communications (mMTC). As the bulk of mMTC will be primarily generated by energy-constrained UE, the benefits brought by S-nodes would substantially simplify both the network and UE design and operation, particularly when caching and aggregating UE traffic.

To achieve the desired results, S-nodes would be primarily placed to enhance capacity wherever active UE traffic is known to exceed the capabilities of macro base stations. Maximizing the placement flexibility of S-nodes entails the utilization of wireless back-hauling, which is realized by scheduling S-node access on macro base stations using the same radio frequency resources connecting UE. The utilization of radio frequency resources is then enhanced by exploiting the proximity of UE to S-nodes capitalizing on the relaxed size and energy constraints at S-nodes. For example, while most UE are limited to utilizing a maximum of 2x2 MIMO transmission, an S-node would be able to utilize higher-order MIMO transmission modes which can theoretically scale the system capacity. The well behaved nature of the S-node’s wireless channel also enhances the potential for new multiple antenna techniques such as CoMP, as described in figure 1.5.

Figure 1.5: Users connecting on second tier leverage higher capacity
1.4 Thesis Contribution and Outline

This thesis aims to verify the benefits of Two-Tier connectivity as a viable solution for enhancing the capacity of cellular communication systems while quantifying the gains and limitations associated with the Two-Tier connectivity paradigm. Two-Tier gains will be verified through the simulation of contemporary cellular communication networks using a series of realistic assumptions. Systems utilizing a pure macrocell layout will be compared to augmented Two-Tier networks.

The Two-Tier architecture is a new network architecture, and hence requires a good understanding from the perspective of a mobile network operator. We are addressing where to place the S-nodes, what we stand to gain from concentrating mobile traffic using them, and how these vary across different network scenarios. The main contribution in this thesis is how the first tier link, between the macrocell station and the S-node, influences the network capacity and coverage leveraging its well behaved wireless profile and potential for higher spectral utilization. This is in contrast to the large pool of research on networking relays [2] [3], where joint transmissions over multiple hops are studied and optimized jointly at the different hops.

The rest of this thesis is organized as follows. Chapter 2 lays out the utilized system model. Chapter 3 details the necessary provisions for the introduction of Two-Tier S-nodes. A summary of the simulation is discussed at the end of Chapter 3 to facilitate the reproduction of this work. Chapter 4 provides simulation results and analysis, followed by the conclusions of the thesis in Chapter 5.
Chapter 2

System Model

Assessing the performance of a cellular communication system would ideally be performed by setting up a physical network with the configurations under consideration along with the proposed solutions, which would then be evaluated under realistic usage to validate the feasibility of proposals under consideration. However, such an approach is seldom feasible which necessitates the utilization of computer simulations to evaluate the performance of contemporary cellular communication systems. Under such an approach, the working assumptions for systems under consideration are modeled to emulate realistic usage. In this thesis, a practical 4G baseline model is utilized for a single tier system and is later on expanded to account for Two-Tier deployment configurations.

2.1 System Layout and Frequency Bands

A hexagonal layout of macrocells is assumed and shown in Figure 2.1. The system layout consists of two rings of surrounding interfering cells for a total of 19 macrocells. To provide an accurate measure of interference at all parts of the network, a wraparound distance calculation is utilized and shown in Figure 2.2. For example, a cell in the top left end of the network is logically adjacent to the bottom right cell and so on such that the
maximum distance between any two entities in this scheme would be about four times
the cell radius.

Figure 2.1: Hexagonal grid representation of a single-tier macro cell network with users
uniformly distributed

Figure 2.2: Distances using wraparound method
The frequency bands under consideration comprise a subset of frequency bands typically utilized by mobile network operators and include low, mid and high frequency bands, such as:

- Band 2 (PCS): UL 1900 MHz, DL 2000 MHz (20 to 40 MHz channels)
- Band 4 (AWS): UL 1700 MHz, DL 2100 MHz (20 to 40 MHz channels)
- Band 5 (CLR): UL 800 MHz, DL 800 MHz (10 to 15 MHz channels)
- Band 7: UL 2540 MHz, DL 2660 MHz (40 to 80 MHz Channels)
- Band 12: UL 700 MHz, DL 700 MHz (10 to 15 MHz Channels)
- Band 42 (TDD): 3500 MHz (100 MHz Channels)

As Figures 2.1 and 2.2 show, a macro base station is placed at the centre of each cell with three transmission sectors. The beam pattern of each sector is defined in section 4 of 3GPP TR 36.942 as follows

\[ A(\Theta) = \min\{12\left(\frac{\Theta}{\Theta_{3dB}}\right)^2, A_m\} \quad \text{where} \quad -180 \leq \Theta \leq 180 \]  

(2.1)

Here \( \Theta \) is the beam angle, \( \Theta_{3dB} \) is the beam angle at which the beam power is half of its maximum value, and \( A_m \) is the maximum beam amplitude. In our system these are assigned as

\[ A_m = 20dB \]  

(2.2)

\[ \Theta_{3dB} = 65^\circ \]  

(2.3)
Using the equation above, 2.1, the macro base station antenna pattern is plotted in polar coordinates in Figures 2.3 and 2.4.

Figure 2.3: Antenna gain pattern for a base station transmission sector. 3GPP 25.996 [11]

2.2 User Distribution and Mobility

The number of users in the system is assumed to be 30 users per cell, giving a total of 570 system users, that are dropped, i.e. assigned a location on the grid, randomly using a uniform distribution. The initial drop emulates the scattering of user locations in a real environment when accessing a cellular communication network, and is a starting point for the simulations. User locations are then updated based on the mobility profile followed through the temporal execution of the simulation as shown in Figure 2.5.
The mobility parameters are chosen to model realistic user movements throughout the network using a probabilistic distribution of the user angle of movement and velocity. The angle of movement is assumed to be uniformly distributed between 0 and 360 degrees. The velocity depends on the user profile chosen, which in the case of our model is 3 km/h following the pedestrian mobility profile detailed in 3GPP 25.996. [11]

A uniform user mobility profile will result in a Poisson point process of system users, i.e. for any area inside the considered two-dimensional grid, the number of users inside that area will follow a Poisson distribution [10]. The ratio of users inside that area vs total system users will also match the same ratio as the area vs the total grid. For
Figure 2.5: Randomized user mobility modeled in simulations

example, taking a circle with one quarter the area of the total system grid and averaging
the number of users inside that area over time will result in a number equal to a quarter
of the total number of users in the system. I.e., for a region $B \subset \mathbb{R}^2$:

$$P\{N(B) = n\} = \frac{(\lambda|B|)^n}{n!}e^{-\lambda|B|}$$  \hspace{1cm} (2.4)

Where $\lambda > 0$ is the homogeneous Poisson process’ parameter, $|B|$ denotes the area of
$B$ and $N(B)$ denotes the number of points in the region $B$.

In a Two-Tier system where we model users that are clustered together, this spatial
distribution is maintained in a scaled and disjointed form. The users clustered around
each hot spot follow a uniform distribution scaled along the radius toward that hot spot,
but are independent from other users in the network.
Chapter 2. System Model

2.3 Simulation Structuring

Simulations are structured to run in two nested loops, with the inner loop iterating over 1 millisecond timeframes, to match the LTE slot duration, while generating the instantaneous fast fading parameters. The outer loop iterates over 10 millisecond timeframes, to match the LTE frame duration, and updates the pathloss and shadow fading parameters. A snapshot of the system is taken once every iteration in the inner loop, i.e. once every 1 millisecond, and the SINR is calculated for all users. SINR values are then mapped to the achievable throughput rates using the Alpha-Shannon formula [13]. For any system configuration, simulation run for up to 100 seconds, i.e. 100,000 snapshots are used to simulate any configuration.
Figure 2.7: Uniform distribution of users in a regular cell

Figure 2.8: Uniform distribution of users subsequently clustered at hot spots
In the outer loop iteration of the system simulations, users are assigned to the base station providing the strongest received signal power. The received signals from all two rings of interfering cells are used to calculate the instantaneous SINR for each inner loop iteration. Specifically, the received signals are calculated based on the transmitted power of each base station (BS), antenna gains, beamforming gains when applicable, path loss and fading. A record of the distance between all pairs in a two dimensional matrix is kept and updated at each outer loop iteration in the system simulation. This distance is used to compute the channel metrics for each of the mentioned pairs in the system.

2.4 Propagation Environment

To emulate practical system deployments, the adopted macrocell pathloss model is based on the COST231 Hata urban propagation model recommended by 3GPP TR 25.996 [11].

\[
\begin{align*}
PL(db) &= (44.9 - 6.55\log_{10}(h_{bs}))\log_{10}\left(\frac{d}{1000}\right) + 45.5 \\
&+ (35.46 - 1.1h_{ms})\log_{10}(f_c) - 13.82\log_{10}(h_{bs}) + 0.7h_{ms} + C
\end{align*}
\]

(2.5)

In this equation, \(h_{bs}\) refers to the base station antenna height relative to rooftops, \(h_{ms}\) refers to UE height, and \(f_c\) refers to the carrier frequency.

For example, for base station antenna height \(h_{bs}\) of 30 m and average user height \(h_{ms}\) of 1.5 m the pathloss is equal to:

\[
PL(db) = 24 + 33.81\log_{10}(f_c) + 35.28\log_{10}(d)
\]

Using a carrier frequency \(f_c\) of 2 GHz, pathloss can be calculated as:
\[ PL_{db} = 135.57 + 37.6\log_{10}(d) \]

And for 800 MHz the pathloss becomes:

\[ PL_{db} = 122.15 + 37.6\log_{10}(d) \]

These parameters can be selected based on the environment which is being considered, along with the cell radius and log normal shadow fading parameters. The following table specifies typical values of the parameters utilized to describe the main deployment scenarios for macro cellular communication systems - namely the dense urban, urban, suburban and rural deployment scenarios:

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Cell Radius (m)</th>
<th>Log Normal Std Dev (dB)</th>
<th>Transmitter height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dense Urban</td>
<td>500</td>
<td>10</td>
<td>25</td>
</tr>
<tr>
<td>Urban</td>
<td>750</td>
<td>8</td>
<td>30</td>
</tr>
<tr>
<td>Suburban</td>
<td>1000</td>
<td>8</td>
<td>30</td>
</tr>
<tr>
<td>Rural</td>
<td>1500</td>
<td>6</td>
<td>70</td>
</tr>
</tbody>
</table>

### 2.5 Channel Model

The adopted channel model is derived from the MIMO channel model presented in 3GPP TR 25.996, in which both the transmitter and receiver are assumed to utilize a linear antenna array. While UE typically utilize two antenna elements, both base stations and S-node can utilize up to 64 elements in this model.

Between each transmitter and receiver pair, wireless signals propagating from the
transmitter reflect off the surrounding environment before landing at the receiver. This spatial profile is modeled mathematically by assigning a set of paths, with angles of departure and arrival at the transmitter and receiver sides, respectively as shown in Figure 2.9. These paths exist between every transmitter and receiver pair in the system, with the number of paths being defined by the utilized model. The number of paths, N, indicated in the model for any specific choice of environment entails up to N resolvable spatial signal components between the transmitter and receiver pair. For example, urban macrocell environments are typically profiled as having N=6. When simulating instances of wireless channels between transmitters and receivers, the parameters for each path will be randomly selected and are practically dependent on the physical characteristics of the environment and how the reflecting objects are positioned.

![Figure 2.9: Channel modeling](image)

The adopted MIMO channel model, detailed in Figure 2.10, also follows the specifications provided in 3GPP TR 25.996 [11]. This link model assumes 6 signal paths, with the corresponding relative path power and delays detailed in the chart of Figure 2.5. Specifically, the link level parameters referred to as Case III, also known as Case D in 3GPP designators [11] or Model B in 3GPP2 designators are utilized.
### Chapter 2. System Model

#### Table 2.10: 3GPP 25.996, showing various physical parameters for link level channel model used in system simulations. [11]

<table>
<thead>
<tr>
<th>Model</th>
<th>Case I</th>
<th>Case II</th>
<th>Case III</th>
<th>Case IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corresponding 3GPP Designator*</td>
<td>Case B</td>
<td>Case C</td>
<td>Case D</td>
<td>Case A</td>
</tr>
<tr>
<td>Corresponding 3GPP2 Designator*</td>
<td>Model A, D, E</td>
<td>Model C</td>
<td>Model B</td>
<td>Model F</td>
</tr>
<tr>
<td>PDP</td>
<td>Modified Pedestrian A</td>
<td>Vehicular A</td>
<td>Pedestrian B</td>
<td>Single Path</td>
</tr>
<tr>
<td># of Paths</td>
<td>4+1 (LOS on, K = 8dB)</td>
<td>6</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>Delay (μs)</td>
<td>1) 0.0 2) -Inf</td>
<td>0</td>
<td>0.0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>1) -6.51 2) 0.0</td>
<td>0</td>
<td>1.0</td>
<td>310</td>
</tr>
<tr>
<td></td>
<td>1) -16.21 2) -9.7</td>
<td>110</td>
<td>-9.0</td>
<td>710</td>
</tr>
<tr>
<td></td>
<td>1) -25.71 2) -19.2</td>
<td>190</td>
<td>-10.0</td>
<td>1090</td>
</tr>
<tr>
<td></td>
<td>1) -29.31 2) -22.8</td>
<td>410</td>
<td>-15.0</td>
<td>1730</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-20.0</td>
<td>2510</td>
</tr>
<tr>
<td>Speed (km/h)</td>
<td>1) 3 2) 30, 120</td>
<td>3, 30, 120</td>
<td>3, 30, 120</td>
<td>3</td>
</tr>
<tr>
<td>Topology</td>
<td>Reference 0.5λ</td>
<td>Reference 0.5λ</td>
<td>Reference 0.5λ</td>
<td>N/A</td>
</tr>
<tr>
<td>PAS</td>
<td>1) LOS on: Fixed AoA for LOS component, remaining power has 360 degree uniform PAS. 2) LOS off: PAS with a Laplacian distribution, RMS angle spread of 35 degrees per path</td>
<td>RMS angle spread of 35 degrees per path with a Laplacian distribution or 360 degree uniform PAS</td>
<td>RMS angle spread of 35 degrees per path with a Laplacian distribution</td>
<td>N/A</td>
</tr>
<tr>
<td>DoT (degrees)</td>
<td>0</td>
<td>22.5</td>
<td>-22.5</td>
<td>N/A</td>
</tr>
<tr>
<td>AoA (degrees)</td>
<td>22.5 (LOS component) 67.5 (all other paths)</td>
<td>67.5 (all paths)</td>
<td>22.5 (odd numbered paths), -67.5 (even numbered paths)</td>
<td>N/A</td>
</tr>
<tr>
<td>Node B/Base Station</td>
<td>Topology</td>
<td>Reference: ULA with 0.5λ-spacing or 4λ-spacing or 10λ-spacing</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PAS</td>
<td>Laplacian distribution with RMS angle spread of 2 degrees or 5 degrees, per path depending on AoA/AoD</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td></td>
<td>AoD/AoA (degrees)</td>
<td>50° for 2° RMS angle spread per path 20° for 5° RMS angle spread per path</td>
<td>N/A</td>
<td></td>
</tr>
</tbody>
</table>

*Designators correspond to channel models previously proposed in 3GPP and 3GPP2 ad-hoc groups.
2.6 Channel Matrix Calculation

As described in section 1.2, the MIMO channel offers gains in capacity of up to a factor of the number of antenna elements on the smaller of the ends of the wireless link. To generate the MIMO channel matrix of coefficients, the guidelines from 3GPP 25.996 [11] are used. These steps will be described in further detail below.

The approach followed is to generate realizations of each of the user parameters required in computing channel coefficients in a step by step process. Certain environment parameters are assumed under the models provided in table 5.1 of [11] as shown in 2.11.

<table>
<thead>
<tr>
<th>Channel Scenario</th>
<th>Suburban Macro</th>
<th>Urban Macro</th>
<th>Urban Micro</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of paths (N)</td>
<td>6</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Number of sub-paths (M) per-path</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Mean AS at BS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AS at BS as a lognormal RV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma_{\text{AS}} = 10^{-1}\left(\varepsilon_{\text{AS}}x + \mu_{\text{AS}}\right), x \sim \eta(0,1)$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E(\sigma_{\text{AS}}) = 5^0$</td>
<td>$1^0$</td>
<td>$1^0$</td>
<td>$1^0$</td>
</tr>
<tr>
<td>$\mu_{\text{AS}} = 0.69$</td>
<td>$0.810$</td>
<td>$0.810$</td>
<td>$0.810$</td>
</tr>
<tr>
<td>$\sigma_{\text{AS}} = 0.13$</td>
<td>$0.34$</td>
<td>$0.34$</td>
<td>$0.34$</td>
</tr>
<tr>
<td>$\mu_{\text{AS}} = 1.18$</td>
<td>$1.18$</td>
<td>$1.18$</td>
<td>$1.18$</td>
</tr>
<tr>
<td>$\sigma_{\text{AS}} = 0.210$</td>
<td>$0.210$</td>
<td>$0.210$</td>
<td>$0.210$</td>
</tr>
<tr>
<td>NLOS: $E(\sigma_{\text{AS}}) = 1^0$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N/A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\gamma_{\text{AS}} = \sigma_{\text{AD}}^2 / \sigma_{\text{AS}}$</td>
<td>$2^0$</td>
<td>$1^0$</td>
<td>N/A</td>
</tr>
<tr>
<td>Per-path AS at BS (Fixed)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BS per-path AoD Distribution</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>lognormal standard distribution</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\eta(0, \sigma_{\text{AD}}^2)$ where $\sigma_{\text{AD}} = r_{\text{AS}}G_{\text{AS}}$</td>
<td>$\eta(0, \sigma_{\text{AD}}^2)$ where $\sigma_{\text{AD}} = r_{\text{AS}}G_{\text{AS}}$</td>
<td>$\sigma_{\text{AD}} = r_{\text{AS}}G_{\text{AS}}$</td>
<td>$\eta(0, \sigma_{\text{AD}}^2)$ where $\sigma_{\text{AD}} = r_{\text{AS}}G_{\text{AS}}$</td>
</tr>
<tr>
<td>$\gamma_{\text{AD}} = 1^0$</td>
<td>$1^0$</td>
<td>$1^0$</td>
<td>$1^0$</td>
</tr>
<tr>
<td>$\gamma_{\text{AD}} = 40^0$</td>
<td>$40^0$</td>
<td>$40^0$</td>
<td>$40^0$</td>
</tr>
<tr>
<td>Delay spread as a lognormal RV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma_{\text{DS}} = 10^{-1}\left(\varepsilon_{\text{DS}}x + \mu_{\text{DS}}\right), x \sim \eta(0,1)$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mu_{\text{DS}} = -6.80$</td>
<td>$-6.18$</td>
<td></td>
<td>N/A</td>
</tr>
<tr>
<td>$\sigma_{\text{DS}} = 0.18$</td>
<td>$0.18$</td>
<td></td>
<td>N/A</td>
</tr>
<tr>
<td>Mean total RMS Delay Spread</td>
<td>$0.17 \mu$s</td>
<td>$0.65 \mu$s</td>
<td>$0.251 \mu$s (output)</td>
</tr>
<tr>
<td>$\tau_{\text{DS}} = \sigma_{\text{DS}} / G_{\text{DS}}$</td>
<td>$1.4$</td>
<td>$1.7$</td>
<td>N/A</td>
</tr>
<tr>
<td>Distribution for path delays</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lognormal shadowing standard deviation, $\sigma_{\text{SF}}$</td>
<td>$8$dB</td>
<td>$8$dB</td>
<td>NLOS: $10$dB</td>
</tr>
<tr>
<td>Pathloss model (dB), d is in meters</td>
<td>$31.5 + 35\log_{10}(d)$</td>
<td>$31.5 + 35\log_{10}(d)$</td>
<td>NLOS: $34.53 + 38\log_{10}(d)$</td>
</tr>
<tr>
<td>NLOS: $34.53 + 38\log_{10}(d)$</td>
<td>$31.5 + 35\log_{10}(d)$</td>
<td>$31.5 + 35\log_{10}(d)$</td>
<td>NLOS: $34.53 + 38\log_{10}(d)$</td>
</tr>
</tbody>
</table>

Figure 2.11: 3GPP 25.996, showing various physical parameters for link level channel model used in system simulations. [11]

Recalling the cell layout previously described, locations are determined by dropping
users across the network. Furthermore, every cycle of the outer loop of our system simulation updates the UE locations based on UE mobility profiles. The distances between each UE and base station are then calculated using those relative locations, using a wraparound method where for example, a UE on the bottom right of the simulation space will be measured roughly one cell away from the top left base station by wrapping them around as was prescribed in Section 2.1.

Using the methods described, the closest distances between each user and base station pair are calculated within a matrix as shown below. Each row corresponds to one user and each column to one base station.

\[
\begin{bmatrix}
  d_{1,1} & d_{1,2} & \ldots & d_{1,19} \\
  d_{2,1} & d_{2,2} & \ldots & d_{2,19} \\
  \vdots & \vdots & \ddots & \vdots \\
  d_{570,1} & d_{570,2} & \ldots & d_{570,19}
\end{bmatrix}
\]

As a result of the locations generated based on user velocity and movement direction, the angle of the line of sight (LOS) path is defined relative to each component, $\theta_{BS}$ for the base station, and $\theta_{MS}$ for the UE. User location is then updated for the subsequent system snapshots, in a similar manner with velocity randomly generated within the defined user mobility profile. Specifically, the magnitude of velocity $|v|$ is uniformly selected between zero and the UE profile velocity while the direction of velocity $\theta_v$ is selected uniformly between 0 and $2\pi$.

Using the path loss equations previously described, which differ for each frequency
band and deployment environment defined by the previously specified parameters (base station height, etc), the path loss for each UE - eNB pair is determined by transforming the distance matrix to generate a matrix of the same dimensions. The SINR for each UE is then determined using the path loss for each UE - eNB pair.

$$
\begin{bmatrix}
PL_{1,1} & PL_{1,2} & \ldots & PL_{1,19} \\
PL_{2,1} & PL_{2,2} & \ldots & PL_{2,19} \\
\vdots & \vdots & \ddots & \vdots \\
PL_{570,1} & PL_{570,2} & \ldots & PL_{570,19}
\end{bmatrix}
$$

2.7 Throughput Calculation

The Alpha-Shannon formula is employed to approximate the mapping of UE SINR to the corresponding Modulation and Coding Schemes (MCS)

$$
\text{Throughput} = \begin{cases} 
0, & \text{for } \text{SINR} < \text{SINR}_{\text{min}} \\
\alpha \cdot S(\text{SINR}), & \text{for } \text{SINR}_{\text{min}} < \text{SINR} < \text{SINR}_{\text{max}} \\
\text{Thr}_{\text{max}}, & \text{for } \text{SINR}_{\text{max}} < \text{SINR}
\end{cases}
$$

where \( S(\text{SINR}) = \log_2(1 + \text{SINR})(\text{bps/Hz}). \)

The attenuation factor \( \alpha \) shows how close of a rate can be achieved to Shannon’s bound for the channel. The following values are assumed based on the recommendation in [13]:

$$\alpha = 0.75 \quad (2.6)$$
\begin{align*}
\text{SINR}_{\text{min}} &= -6.5 \text{ dB} \\
\text{SINR}_{\text{max}} &= 17 \text{ dB}
\end{align*} (2.7) (2.8)

### 2.8 Resource Allocation

Following the LTE standard procedures, radio frequency resources are assigned to users once every 10 milliseconds. The radio resource grid illustrated in figures 2.11 and 2.12 showcase the time-frequency domains in which physical channels carrying user and control messages are scheduled in. Depending on the channel bandwidth selected, the frequency axis can extend to accommodate up to 100 radio blocks. With other factors being constant, the more radio resources allocated to a communication link, the higher the achievable throughput rate. [1], [9]. Radio resources designated for the Physical Downlink Shared Channel (PDSCH) are utilized for downlink data traffic [12], with the mapping of these resources being determined by the utilized scheduling algorithm, which typically maximizes a utility metric for each radio resource at each point in time. Allocation of radio frequency resources to system users in contemporary cellular systems is commonly facilitated by a proportional fair scheduler that balances the objective of maximizing resource utilization with maintaining the connectivity of users utilizing the weakest links in the network.

### 2.9 Proportional Fair Scheduling

In Proportional Fair Scheduling (PFS), the historical allocation of resources to system users is recorded and users are prioritized at any scheduling interval based on how well they do when compared to their averaged performance to maximize the throughput rate for each user over time. The prioritization metric for each user $i$ in the cellular network
utilizing PFS can be described by the following equation:

\[ P_i = \frac{T_i^\alpha}{R_i^\beta} \]  \hspace{1cm} (2.9)

Here \( T \) is the potential rate that the user can achieve, and \( R \) is the historical average achieved by that user. The parameters \( \alpha \) and \( \beta \) are used to tune the fairness of the scheduler. Having \( \alpha = 0 \) and \( \beta = 1 \) results in a round robin algorithm, while the opposite \( \alpha = 1 \) and \( \beta = 0 \) results in maximum throughput scheduling. We use \( \alpha = 1 \) and \( \beta = 1 \) in our system model to achieve proportional fair scheduling.
Figure 2.13: LTE resource grid \[12\]
Chapter 3

Modelling and Design

Considerations for Two-Tier Cellular Communication Systems

When compared to conventional heterogeneous cellular layouts, Two-Tier cellular systems offer greater flexibility in capturing user traffic demand as has been discussed in Chapter 1. Subsequently, focus when evaluating Two-Tier systems as an effective paradigm for next generation wireless systems is centered around quantifying the gains resulting from this increased flexibility.

3.1 Clustering Users at the S-nodes

In the alternative Two-Tier system structure, a set of clustered users utilize an S-node as a common gateway to access system base stations. User connectivity to S-nodes will be based on specific criterion discussed herein.

A fair assumption is that the air interface on the second tier can utilize unlicensed spectrum using other interfaces such as WiFi or Bluetooth. Given the large bandwidths provided by unlicensed bands, any link closer than 10 meters is assumed to be capable of
providing as much throughput as the S-node can afford based on the first tier connection. In other words, the second tier throughput rate, up to 10 meters from an S-node, will not be a bottleneck for user access. On the other hand, inks extending beyond 10 meters will occupy licensed spectrum. Minding these constraints, we can lay out the policy of connecting to S-nodes as such:

- Users closer than 10 meters can all connect.
- Users closer than X meters can connect if it is deemed to be more efficient for the system resource usage as a whole for them to be on the S-node as opposed to connecting directly to the eNB.
- The total number of users connected shouldn't exceed Y (capacity of users at S-node).
- The total second tier traffic should not exceed what the first tier can allocate on its link to the S-node.

Minding these policies, and assuming global knowledge of downlink SINR and the resulting potential throughput along with user locations, The following method is used to group users:

- Sort users by distance to S-node.
- For users closer than 10 meters, add them one by one in order for as long as we don’t exceed the S-node’s available resources.
- For users further than 10 meters away, sort them by eligibility metric.
- Add users one by one, in order of decreasing eligibility until 0 is reached, as long the capacity of an S-node is not exceeded.
A positive eligibility metric indicates that the system is better off in terms of resources if it offloads to the S-node while a non-positive metric indicates the opposite. Additionally, a higher eligibility value would correspond to a higher offloading gain.

\subsection{Dispersion Index - Clustering Criteria}

Using the standard method of dropping users in a system simulation will result in a Poisson distribution as discussed in Chapter 2. We can change the mobility of our users using different models that will produce a more clustered distribution. Our work evaluates how the benefits of the Two-Tier system can be greater in such a distribution. This takes advantage of the arrangement of the network in use cases where the Two-Tiered system is primarily intended for.

In the baseline system, the way we generate user locations is a uniform distribution in two dimensions. We run a loop iterating over each user and generating random X and Y positions for each user independently. Due to our hexagonal layout of cells, we are generating coordinates in a rectangle that totally encompasses the 19 cells of our system. So to avoid dropping users outside of that area, we generate random coordinates for those again until they fall into the 19 cells. This has been verified to maintain uniformity in spatial distribution.

To modify this distribution, we would like to move from a uniform spatial distribution of user coordinates toward a model which demonstrates more clustering at certain spots. This is based on the assumption that some locations such as offices, bus stops, landmarks, etc attract larger concentrations of users. We will show there is even more benefit to using this Two-Tier framework when considering these situations.
We have devised two approaches to model this distribution. The first is a less intuitive but computationally efficient method, called the contraction method. In both methods we first drop S-nodes across the system grid in a spatially uniform distribution. In the contraction method, we generate uniformly distributed locations for all of the user terminals, randomly assign each user to an S-node, and contract the distance between them by a factor of 10. This results in a user distribution biased towards the S-nodes. Changing the contraction factor or clustering factor between 1-20 can demonstrate a varying bias.

The second method is to choose a radius around each S-node, and have the user density increase from the border toward the centre of the chosen area. A fraction of the user terminals will be uniformly distributed outside of these areas with a lower density. We do not employ this method in our work due to an excess of parameters that must be arbitrarily chosen, and will make the results difficult to compute.

Users in a network are dispersed to the extent that they are not contracted together, therefore the dispersion index may be defined as the inverse of the contraction, or clustering factor. A dispersion index of zero means infinite contraction of users around the concentrating node, therefore they will all be in one spot. A dispersion index of one which is also a contraction factor of one means users are uniformly distributed with regards to the concentrating nodes. In the figures 4.19 to 3.5, the differences in geometric distributions for different clustering factors are illustrated. To better represent practical deployment scenarios, the conservative clustering factors of 1 and 10 are considered when evaluating Two-Tier cellular communication systems.
3.3 Modified System Simulation for Two-Tier Evaluation

At this point we want to evaluate our Two-Tier framework against single tier based on 3GPP models. A parallel set of matrices traces the throughput rates achieved in the alternative Two-Tier access framework to ensure that any throughput gains can be attributed to the modified framework as opposed to random generation of parameters.

The adopted proportional fair resource allocation scheme is extended to include both S-nodes' backhaul links as well as user terminals that connect directly. Resource allocation to S-nodes is weighted by the number of users they are serving. A coefficient equal to the number of users being served is factored into the proportional fair parameter.

To compute all of the channel instances between base stations and users, we have a 2 dimensional matrix defined with a size of number of base stations by number of users. Any index of this matrix will contain the channel gain between a base station and a user. This matrix undergoes several transformations throughout the computation but we are mainly considering the size, and how to accommodate the second tier of the network into it. In the second tier, the S-nodes take the place of base stations and UEs are in the place of the users.

In the single tier simulations, based on the specifications in Chapter 2, users are first dropped within the hexagonal grid, channel parameters generated for each eNB-UE pair, UEs select the strongest eNB to associate with, then traffic is scheduled in the downlink for each eNB’s cell. This generates a single snapshot for the network throughput. The simulation loops for 10 inner loops to generate snapshots with updated channel values within a frame. This inner loop maintains cell associations and channel coefficients, it
only updates the time as each inner loop progresses by 1 millisecond.

The outer loop of the simulation then loops for as long as needed to acquire enough snapshots. In this work we used 10,000 outer loops. Each instance of the outer loop regenerates the UE locations based on velocity and the randomized direction of movement, as well as subsequently regenerating the channels and scheduling users.
Figure 3.1: Clustering with contraction parameter of 1 (uniform)

Figure 3.2: Clustering with contraction parameter of 5

Figure 3.3: Clustering with contraction parameter of 10

Figure 3.4: Clustering with contraction parameter of 15

Figure 3.5: Clustering with contraction parameter of 20
Chapter 4

Simulation Results

Depending on the key applications and use cases, a wide range of metrics can be utilized for evaluating the performance of cellular communication systems. When considering throughput rates, the following metrics are typically considered for system performance evaluation:

- Peak cell throughput: The maximal throughput achieved at any system cell.
- Peak user throughput: The maximal throughput achieved by any system user.
- Mean/average cell throughput: The average throughput at system cells.
- Mean/average user throughput: The average throughput experienced by system users.
- Median throughput: The fiftieth percentile throughput of system users, derived from the system user throughput CDF, representing the overall performance of system users.
- Cell edge throughput: The fifth percentile throughput of system users, derived from the system user throughput CDF, representing the performance of system users at cell edges.
Additional parameters, such as cell and system capacity, can be derived from system throughput rates. For the systems under consideration, peak throughput rates seldom reflect user experienced performance and are thus omitted from the evaluation. Average cell throughput rates were also omitted as having a few well-connected users can bias the results when adopting that metric. To mitigate the impact of using different transmission bandwidths for different frequency bands, throughput rates were divided by the transmission bandwidth, i.e. the “spectral efficiency” metric was employed to offset transmission bandwidth variations across utilized bands. Low-order MIMO (2x2) is also assumed to focus the comparisons on user offloading and clustering and ensure that reported gains are not attributed to the utilization of high-order MIMO transmission.

4.1 Baseline Performance

The baseline system performance, for the considered frequency bands and deployment scenarios, under single tier deployments is illustrated in Figures 4.1 to 4.12 showcasing the Cumulative Distribution Function (CDF) for system spectral efficiencies to account for varying transmission bandwidths available at different frequency bands. The results, unsurprisingly, verify the utility of lower frequency bands for covering larger cell areas in single tier deployments. While all system users were successfully connected in the Suburban and Rural scenarios when utilizing the 800 MHz frequency band, a substantial proportion of system users, reaching up to 48% of system users, were out of coverage when utilizing the 2600 MHz and 3500 MHz frequency bands, with coverage improving as the cell radius and carrier frequency decrease as detailed in Table 4.1. Similarly, as Table 4.2 verifies, the spectral efficiency for higher frequency bands also increases as the cell radius decreases. On the other hand, the spectral efficiency of lower frequency bands decreases when utilizing smaller cell radii due to increased inter-cell interference. Nevertheless,
the utility of lower frequency bands is severely constrained by the limited transmission bandwidth, with higher frequency bands providing higher median throughput rates than lower frequency bands in all deployment scenarios as detailed in Table 4.3.

Table 4.1: Baseline (Single-Tier) System Coverage for Considered Scenarios and Frequency Bands: Percentage of Connected System Users

<table>
<thead>
<tr>
<th>Deployment Scenario</th>
<th>800 MHz</th>
<th>2600 MHz</th>
<th>3500 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dense Urban</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Urban</td>
<td>100%</td>
<td>100%</td>
<td>91%</td>
</tr>
<tr>
<td>Suburban</td>
<td>100%</td>
<td>88%</td>
<td>73%</td>
</tr>
<tr>
<td>Rural</td>
<td>100%</td>
<td>72%</td>
<td>52%</td>
</tr>
</tbody>
</table>

Table 4.2: Baseline (Single-Tier) User Median Spectral Efficiencies for Considered Scenarios and Frequency Bands

<table>
<thead>
<tr>
<th>Deployment Scenario</th>
<th>800 MHz</th>
<th>2600 MHz</th>
<th>3500 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dense Urban</td>
<td>1.18 bps/Hz</td>
<td>1.83 bps/Hz</td>
<td>1.78 bps/Hz</td>
</tr>
<tr>
<td>Urban</td>
<td>1.42 bps/Hz</td>
<td>1.7 bps/Hz</td>
<td>1.66 bps/Hz</td>
</tr>
<tr>
<td>Suburban</td>
<td>1.77 bps/Hz</td>
<td>1.3 bps/Hz</td>
<td>1 bps/Hz</td>
</tr>
<tr>
<td>Rural</td>
<td>1.6 bps/Hz</td>
<td>1.23 bps/Hz</td>
<td>0.42 bps/Hz</td>
</tr>
</tbody>
</table>

Table 4.3: Baseline (Single-Tier) User Median Throughput Rates for Considered Scenarios and Frequency Bands

<table>
<thead>
<tr>
<th>Deployment Scenario</th>
<th>800 MHz</th>
<th>2600 MHz</th>
<th>3500 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dense Urban</td>
<td>23.6 Mbps</td>
<td>109.8 Mbps</td>
<td>178 Mbps</td>
</tr>
<tr>
<td>Urban</td>
<td>28.4 Mbps</td>
<td>102 Mbps</td>
<td>166 Mbps</td>
</tr>
<tr>
<td>Suburban</td>
<td>35.4 Mbps</td>
<td>78 Mbps</td>
<td>100 Mbps</td>
</tr>
<tr>
<td>Rural</td>
<td>32 Mbps</td>
<td>73.8 Mbps</td>
<td>42 Mbps</td>
</tr>
</tbody>
</table>
Figure 4.1: Baseline system performance: Single tier rural deployment at 800 MHz

4.2 Two-Tier Performance

While Two-Tier connectivity improved the system performance for all scenarios and utilized frequency bands, the largest gains from Two-Tier connectivity were attained when utilizing higher frequency bands over larger coverage areas as detailed in the tables below. The utilization of Two-Tier connectivity, with or without clustering, substantially reduced "coverage gaps" while improving throughput rates, thus enabling the full utilization of mid- and high-frequency in most deployment scenarios.
Figure 4.2: Baseline system performance: Single tier rural deployment at 2600 MHz
Figure 4.3: Baseline system performance: Single tier rural deployment at 3500 MHz
Figure 4.4: Baseline system performance: Single tier suburban deployment at 800 MHz
Figure 4.5: Baseline system performance: Single tier suburban deployment at 2600 MHz
Figure 4.6: Baseline system performance: Single tier suburban deployment at 3500 MHz
Figure 4.7: Baseline system performance: Single tier urban deployment at 800 MHz
Figure 4.8: Baseline system performance: Single tier urban deployment at 2600 MHz
Figure 4.9: Baseline system performance: Single tier urban deployment at 3500 MHz
Figure 4.10: Baseline system performance: Single tier dense urban deployment at 800 MHz
Figure 4.11: Baseline system performance: Single tier dense urban deployment at 2600 MHz
Figure 4.12: Baseline system performance: Single tier dense urban deployment at 3500 MHz
Table 4.4: Two-Tier (Clustering Factor = 1) System Coverage for Considered Scenarios and Frequency Bands: Percentage of Connected System Users

<table>
<thead>
<tr>
<th>Deployment Scenario</th>
<th>800 MHz</th>
<th>2600 MHz</th>
<th>3500 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dense Urban</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Urban</td>
<td>100%</td>
<td>100%</td>
<td>98%</td>
</tr>
<tr>
<td>Suburban</td>
<td>100%</td>
<td>99%</td>
<td>80%</td>
</tr>
<tr>
<td>Rural</td>
<td>100%</td>
<td>89%</td>
<td>66%</td>
</tr>
</tbody>
</table>

Table 4.5: Two-Tier (Clustering Factor = 10) System Coverage for Considered Scenarios and Frequency Bands: Percentage of Connected System Users

<table>
<thead>
<tr>
<th>Deployment Scenario</th>
<th>800 MHz</th>
<th>2600 MHz</th>
<th>3500 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dense Urban</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Urban</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Suburban</td>
<td>100%</td>
<td>100%</td>
<td>93%</td>
</tr>
<tr>
<td>Rural</td>
<td>100%</td>
<td>98%</td>
<td>78%</td>
</tr>
</tbody>
</table>

Table 4.6: Averaged Median Throughput Gains

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Clustering Factor 1 (No Clustering)</th>
<th>Clustering Factor 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dense Urban</td>
<td>106.79%</td>
<td>109.61%</td>
</tr>
<tr>
<td>Urban</td>
<td>111.72%</td>
<td>116.49%</td>
</tr>
<tr>
<td>Suburban</td>
<td>147.49%</td>
<td>151.36%</td>
</tr>
<tr>
<td>Rural</td>
<td>176.89%</td>
<td>179.28%</td>
</tr>
</tbody>
</table>

The significance of Two-Tier gains for rural areas at high frequency bands stem from the potential to eliminate the "digital divide" between the connectivity of urban and rural areas, particularly as rural areas rely exclusively on wireless connectivity in most cases.
Coverage gains achieved by employing a Two-Tier architecture can be seen by visualizing each scenario’s respective coverage on a hexagonal cellular grid.
Chapter 4. Simulation Results

Figure 4.19: Suburban coverage 73% using 3.5 GHz

Figure 4.20: Rural coverage 52% using 3.5 GHz

Figure 4.21: Suburban coverage 80% using 3.5 GHz with Two-Tier

Figure 4.22: Rural coverage 66% using 3.5 GHz with Two-Tier

Figure 4.23: Suburban coverage 93% using 3.5 GHz with Two-Tier for clustered users

Figure 4.24: Rural coverage 78% using 3.5 GHz with Two-Tier for clustered users
Chapter 5

Conclusions and Future Work

5.1 Conclusions

Cellular networks continue to face the challenge of ever increasing demand for additional capacity, which cannot be sustained with conventional macro cell densification, nor can it addressed by augmenting higher frequency bands on existing macro base station infrastructure. The capacity challenge is further complicated when considering the dire need to bridge the connectivity gap between urban and rural areas incapable of benefiting from most urban capacity enhancement solutions. Both heterogeneous and Two-Tier network paradigms have the potential of addressing traffic demand needs and can be viewed as complementary to one another to address all deployment scenarios. This thesis did not aim to argue the case of wireless backhauling Two-Tier networks against wired backhauling heterogeneous networks as future networks can and should leverage both approaches for various deployment scenarios.

The findings of this thesis show that network deification gains, whether realized using the Two-Tier approach or the heterogeneous approach, are enhanced when capturing user clusters generating the largest traffic proportions. Subsequently, the merit of the
Two-Tier approach is emphasized by providing the highest deployment flexibility to capture traffic generated by user clusters. These gains are exemplified in rural areas and at high frequency bands typically supporting the largest transmission bandwidths, which can effectively close the connectivity gap between urban and rural areas - both in terms of service availability and throughput rates.

In addition to substantially enhancing the performance of clustered system users, sparsely distributed users which experience low coverage were also shown to benefit from S-node offloading, either directly by providing improved received signal levels or indirectly by offloading other system users to free up additional radio frequency resources for cell edge users.

5.2 Future Work

The Two-Tier paradigm opens up a multitude of opportunities to evolve wireless network planning. For example, in one of the most trivial extensions of this work, the model proposed in this thesis can be expanded to enable the integration of higher frequency bands, such as millimeter wave, along with a wide range of MIMO transmission modes.
The specific needs of IoT use cases, where focus is shifted towards coverage and energy consumption rather than throughput rates, also constitutes a promising direction for maximizing Two-Tier connectivity gains.

The allocation of spectrum between tiers in this network was assumed to be fixed as focus was centered on demonstrating the merit of added flexibility to capture traffic-generating user clusters. Another apparent area that can be explored would consider the development of frameworks for dynamic resource allocation between tiers. In this case, a mixture of access technologies can be interchangeably employed at the second tier, while also varying the channel bandwidths, carrier combinations, or scheduling algorithms within the utilized spectrum at the first tier.

Finally, the implications of such network architectures on signalling, user handover, as well as user billing, all would benefit can be analyzed from different perspectives to provide a various solution for operators to evolve future network deployments and configurations.
Bibliography


[12] 3GPP TS 36.211, ”Physical channels and modulation”, 2011.
