INTERFERENCE CONSIDERATIONS IN MIMO-BASED
CELLULAR SYSTEMS

by

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ABSTRACT

In this thesis, we consider MIMO-based intra-tier interference in single-tier cellular systems, and inter-tier interference in two-tier femtocellular systems. In single-tier cellular systems, intra-tier interference is a major limiting factor on performance. To mitigate this intra-tier interference, a scheduling algorithm is developed in the presence of an uncertain interference environment. Due to the limited knowledge about the interference, a “margin” is applied in estimating the transmission rate, that is, a backoff from the achievable rate in the previous packet transmission. This algorithm is overly conservative; so, the performance is not satisfying, especially in channels where the fading is relatively uncorrelated from packet to packet. It is difficult to obtain good performance without knowledge of the interference.

For two-tier femtocellular systems, the introduction of femtocells into existing macrocellular systems has the potential to significantly improve the coverage and capacity of these networks. However, the inter-tier interference caused to macrocellular users due to femtocellular transmissions is also a big challenge. In this thesis, the efficacy of applying beamforming (BF) with nulling at the femtocellular base stations (FBSs) is studied in order to mitigate the interference to macrocellular users. The performance of other transmission modes, such as no beamforming and transmit beamforming, are compared with beamforming with nulling, for both macrocellular and microcellular propagation scenarios. Simulation results demonstrate the effectiveness of beamforming with nulling for introducing femtocells with minimal effect on the macrocellular (microcellular) user.
Chapter 1

INTRODUCTION

1.1 Background and Motivation

With the increasing need for high speed wireless applications, future wireless communications will place more demand on reliable high data rate services in dynamic environments [1]. Interference is one of the fundamental limiting factors on the performance of wireless communications in multi-user systems [2]. In a typical cellular system, each base station (BS) serves the mobile stations (MS) in its covering area. Besides the signal sent from the serving BS, an MS can also receive interference from other BSs transmitting on the same frequency. Usually, a cellular system is interference-limited. Fig. 1.1 shows a typical two-cell single-tier cellular system. The signal transmission at a BS can generate interference at MSs in the other cells in the same tier, which is called intra-tier interference [3]-[5]. Fig. 1.2 shows a cellular system with two tiers, in which another tier is introduced to improve the system coverage and capacity; interference from one tier to another tier is called inter-tier interference. Therefore, how to mitigate interference is one key problem in improving the capabilities of wireless services. Moreover, when Multiple-Input and Multiple-Output (MIMO) techniques are incorporated, the interference scenarios become more complicated [6]-[13]. In this thesis, we mainly consider MIMO-based intra-tier interference in single-tier cellular systems, and inter-tier interference in two-tier femtocellular systems.

Our ultimate goal is to develop robust scheduling algorithms that work well in the presence of an uncertain interference environment. Therefore, the impact of
Figure 1.1: A single-tier cellular system.

Figure 1.2: A two-tier cellular system.
different interferers on the desired link needs to be investigated. When studying the performance of an interference-limited system, the signal-to-interference-plus-noise ratio (SINR) is a very important measure. Most of the work done to investigate the impact of MIMO on cellular systems is based on computational-simulation methods. Only a few studies focus on the analysis of the SINR distribution of co-channel MIMO interferers. In [14]-[17], the SINR distribution is derived assuming that all the BSs adopt the same MIMO modes. However, this implementation is unrealistic. To relax this constraint, the impact of different interfering MIMO schemes on other MIMO schemes is studied in [18], which also developed a theoretical derivation of the distribution of the SIR at the receivers with STBC applied at the desired link and different MIMO schemes at the interferers. Based on the distribution of the SIR derived in [18], we develop a simple and conservative scheduling algorithm without knowledge of the interference.

In addition to the interference in single-tier cellular system, interference is an important factor in multi-tier systems, such as in the introduction of femtocells to service indoor users. A femtocell is a low-power, user-deployed BS designed for indoor use, which has the potential to provide improvements in coverage and capacity [19]-[20]. Several papers [21]-[23] discuss the system design of femtocellular systems. The introduction of femtocells into an existing cellular system, however, also brings new challenges [24]-[28]. Although the typical transmit power of a femtocellular base station (FBS) is low, as the number of femtocells within a macrocell increases, the cumulative interference from the FBSs to the macrocellular and other femtocellular users (MUEs and FUEs, respectively) could be significant, and the system performance might deteriorate quickly.

Several recent papers address the interference problem. In [29], the multi-subcarrier nature of OFDMA is considered to cope with this interference. Handling
co-channel and inter-carrier interference by frequency scheduling in OFDMA networks is studied in [30]. In [31], downlink carrier selection and transmit power calibration at femtocells are proposed to manage interference when operating based on 3GPP Release 7 standards. In [25], an uplink capacity analysis and interference avoidance strategy for a CDMA-based femtocell network is provided. Power control is used to mitigate co-channel cross-layer interference in [26] and [27]. In [26], strategies for maximum transmit power adjustment at femtocell users to suppress the interference at the macrocell base stations are presented, and a downlink power control strategy at femtocells, based on a distributed utility-based SINR adaptation, is proposed to alleviate the interference at the macrocell in [27].

Here, the efficacy of beamforming (BF) with nulling is studied in mitigating the interference introduced by femtocells, including the interference from an FBS to an MUE as well as FUEs in other femtocells. Since femtocells should be deployed with minimal interference to the existing macrocellular system, BF with nulling is considered at the FBSs.

In this thesis, we develop a scheduling algorithm in a single-tier cellular system with uncertain interference environment. A margin is introduced to estimate the interference channel condition in the next period based on the measured one. Due to the limited knowledge of the interference, the margin algorithm is conservative, and thus, the benefit of the algorithm is limited. Then, the efficacy of BF with nulling is considered to mitigate inter-tier interference in femtocellular systems. Different transmission techniques are compared at the FBSs. Simulation results show that BF with nulling at the FBSs improves the macrocellular throughput significantly, while the penalty in femtocellular performance is negligible.

1.2 Thesis Outline

The rest of the thesis is structured as follows: In Chapter 2, the impact of co-channel MIMO interference on STBC in the desired link, studied in [18], will be
summarized; and a scheduling algorithm in the presence of an uncertain interference environment will be presented. The inter-tier interference and radio environment in femtocellular systems will be introduced in Chapter 3. In Chapter 4, we study the efficacy of beamforming with nulling technique in mitigating this inter-tier interference. Finally, conclusions and future work are presented in Chapter 5.

1.3 Notations and Abbreviations

In this thesis, we use the following notations and abbreviations:

- $E[X]$ Expected value of $X$
- $\|a\|$ Euclidean norm of vector $a$
- $|a|$ Absolute value of $a$
- $A^H$ Hermitian matrix of $A$
- $A^*$ Conjugate transpose of $A$
- $A^T$ Transpose of $A$
- BS Base Station
- CCI Co-Channel Interference
- CLSM Closed-Loop Spatial Multiplexing
- CSI Channel State Information
- FBS Femtocellular Base Station
- FUE Femtocellular User Equipment
- i.i.d Independent and Identically Distributed
- pdf Probability Density Function
- MIMO Multiple-Input Multiple-Output
- MBS Macrocellular Base Station
- MRT Maximal Ratio Transmission
- MUE Macrocellular User Equipment

5
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>OLSM</td>
<td>Open-Loop Spatial Multiplexing</td>
</tr>
<tr>
<td>SINR</td>
<td>Signal-to-Interference-plus-Noise Ratio</td>
</tr>
<tr>
<td>SIR</td>
<td>Signal-to-Interference Ratio</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal-to-Noise Ratio</td>
</tr>
<tr>
<td>SVD</td>
<td>Singular-Value Decomposition</td>
</tr>
<tr>
<td>TDD</td>
<td>Time Division Duplexing</td>
</tr>
</tbody>
</table>
Chapter 2

SCHEDULING IN THE PRESENCE OF UNCERTAIN INTERFERENCE

In a typical cellular system, as shown in Fig. 2.1, a mobile station (MS) receives signals from other interfering base stations (BS), in addition to the signal sent from the desired BS. To achieve the highest spectral efficiencies, the time, frequency, and spatial resources must be optimally allocated among the users; this, however, requires complex resource allocation algorithms that are highly dependent on knowledge of the instantaneous channel and interference conditions.

Figure 2.1: A typical cellular system.
In order to develop efficient and robust scheduling algorithms in the presence of uncertainties in the interference environment, first, we need to evaluate the impact of this uncertainty and the interference on different link-adaptation algorithms. In Section 2.1, we first summarize the results in [18] on the derivation of the probability density functions (pdf) of the SIR for different desired/interfering combinations. Then, a scheduling algorithm, based on the conclusions in [18] is described in Section 2.2.

2.1 Characterization of Interference in MIMO Cellular Systems

To design an efficient and robust scheduling algorithm, we need to first characterize the interference in a multi-user system which employs multiple antennas that can be used in a variety of modes. One of the most important and promising MIMO schemes, Space-Time Block Coding (STBC) [32]-[33], has been adopted in some wireless standards. Due to its ability to combat fading and co-channel interference (CCI), STBC is a likely mode for use by cell-edge users. In this section, we summarize the results derived in [18] by Li, Cimini, and Himayat quantifying the impact of co-channel MIMO interference on a desired link that uses STBC for base-to-mobile transmission.

Since the SINR is often used to schedule resources, the SINR distributions with various MIMO modes used in the interfering base stations (BSs) is first derived. Several works other than [18] have investigated this problem. In [14] and [15], the focus is on deriving the SINR distribution for maximal ratio combining, and, in [16], the optimum combining is considered. Under the assumption of equal-power interfering BSs, the distributions of the SINR for several diversity techniques are derived in [17]. In [18], it is assumed that each interfering BS uses all of its transmitting antennas to send its own data, and each BS only has knowledge about its own channel state information (CSI). This can be considered as the worst case since the number of interfering BSs is the maximum it can be, and no coordination between different
BSs is permitted. Noise is neglected because the focus is on an interference-limited environment. By deriving the pdf of the SIR for different desired/interfering combinations, the authors show that the possible MIMO modes in the co-channel cells can be grouped into two categories. The first category includes STBC, Open-Loop Spatial Multiplexing (OLSM) and Closed-Loop Spatial Multiplexing (CLSM); the second consists of MIMO Beamforming (MBF) and Maximal Ratio Transmission (MRT). Next, we describe the system model used in [18] and present the SIR and pdf of the SIR for the two categories.

2.1.1 System Model

Assume that there are $K$ interfering co-channel cells surrounding a desired cell, and that all the transmitters and receivers are equipped with two antennas. In the desired link, the Alamouti code is used in the transmitter. During the first symbol period, $s_{k,1}$ and $s_{k,2}$ are coded and transmitted from the two antennas of the $k$th ($k = 0, 1, \cdots, K$) BS. The index '0' designates the desired link. In the next symbol period, $s_{k,3}$ and $s_{k,4}$ are sent simultaneously. (In the case of MRT or MBF, only one symbol is sent during one period.) Since the desired BS adopts and STBC mode, $s_{0,3} = -s_{0,2}^*$ and $s_{0,4} = -s_{0,1}^*$.

The baseband signals received at the $i$th ($i = 1, 2$) antenna during two consecutive symbol periods can be written as

$$
\begin{bmatrix}
{r}_{i,1} \\
{r}_{i,2}
\end{bmatrix} = \sqrt{\frac{P_0}{2}} \begin{bmatrix}
{s}_{0,1} & s_{0,2} \\
-s_{0,2}^* & s_{0,1}^*
\end{bmatrix} \begin{bmatrix}
{h}_{0,i1} \\
{h}_{0,i2}
\end{bmatrix} + \sum_{k=1}^{K} \sqrt{\frac{P_k}{2}} \begin{bmatrix}
{s}_{0,1} & s_{0,2} \\
-s_{0,2}^* & s_{0,1}^*
\end{bmatrix} \begin{bmatrix}
{w}_{k,11} & {w}_{k,12} \\
{w}_{k,21} & {w}_{k,22}
\end{bmatrix} \begin{bmatrix}
{h}_{k,i1} \\
{h}_{0,i2}
\end{bmatrix},
$$

(2.1)

where $h_{k,ij}$ ($k = 0, 1, \cdots, K; ij = 1, 2$) is the complex channel gain between the $i$th receiving antenna at the desired receiver and the $j$th transmitting antenna in the $k$th BS. In a rich scattering environment, \{$h_{k,ij}$\} can be modeled as i.i.d. complex Gaussian random variables with zero mean and unit variance. $W_k = \begin{bmatrix}
{w}_{k,11} & {w}_{k,12} \\
{w}_{k,21} & {w}_{k,22}
\end{bmatrix}$
(\(k = 0, 1, \cdots, K\)), which depends on the specific MIMO mode used in the \(k\)th interfering BS, is the precoding matrix used at the \(k\)th BS.

### 2.1.2 SIR Distribution with Different Co-channel MIMO Interferers

#### 2.1.2.1 First Category Interferers

When all the interfering BSs adopt STBC, no precoding is used in the interfering links. In this case, the precoding matrix \(W_k\) is an identity matrix. Moreover, when multiple antennas are available in the desired receiver, maximal ratio combining (MRC) is used to enhance the performance of the system. With two transmit and two receive antennas, and assuming all the interferers have the same power \(P_k = P_I(k = 1, \cdots, K)\), the post-processing SIR at the desired receiver is

\[
\gamma_{\text{STBC-STBC}} = \frac{\eta \cdot |a_0^H a_0|}{\sum_{k=1}^{K} (|a_0^H b_{k1}|^2/|a_0^H a_0| + |a_0^H b_{k2}|^2/|a_0^H a_0|)}, \tag{2.2}
\]

where \(\eta = P_0/P_I\), \(a_0 = \begin{bmatrix} h_{0,11}^* & h_{0,12} \end{bmatrix}^T\), \(b_{k1} = \begin{bmatrix} h_{k,11}^* & h_{k,12} \end{bmatrix}^T\), and \(b_{k2} = \begin{bmatrix} h_{k,11} & h_{k,12} \end{bmatrix}^T\). The variable \(x_0 = |a_0^H a_0|\) has a chi-square distribution and the pdf is \(f_{x_0}(x_0) = \frac{x_0^{2\times2-1}e^{-x_0}}{\Gamma(2\times2)}\), and \(y_k = |a_0^H b_{ki}|^2/|a_0^H a_0| (i = 1, 2)\) has an exponential distribution with pdf \(f_{y_k} = e^{-y_k}\). After some manipulations, it can be shown [18] that the pdf of the SIR in (2.2) is

\[
f_\gamma(\gamma) \approx \frac{1}{\eta \cdot \Gamma(NM + NK) (\gamma/\eta)^{NM-1}} \cdot \frac{\Gamma(NM + NK) (\gamma/\eta)^{NM+NK}}{\Gamma(NM + NK)(1 + \gamma/\eta)^{NM+NK}}, \tag{2.3}
\]

where \(\gamma \geq 0\), and \(N\) and \(M\) are respectively the number of transmit and receive antennas.

When OLSM is used in the interfering links, no precoding is needed. With \(a_{0,1} = \begin{bmatrix} h_{0,11} & h_{0,21} \end{bmatrix}^T\), \(a_{0,2} = \begin{bmatrix} h_{0,12} & h_{0,22} \end{bmatrix}^T\), \(a_{k,1} = \begin{bmatrix} h_{k,11} & h_{k,21} \end{bmatrix}^T\), and \(a_{k,2} = \begin{bmatrix} h_{k,12} & h_{k,22} \end{bmatrix}^T\), the post-processing SIR at the desired mobile can be derived as

\[
\gamma_{\text{STBC-OLSM}} = \frac{\eta \cdot (|a_{0,1}^H a_{0,1}| + |a_{0,2}^H a_{0,2}|)}{\sum_{k=1}^{K} \frac{|a_{0,1}^H a_{0,1}| + |a_{0,2}^H a_{0,2}|}{|a_{0,1}^H a_{0,1}| + |a_{0,2}^H a_{0,2}|}}, \tag{2.4}
\]
and the pdf is the same form as in (2.3) [18].

When CLSM is used by the interferer, the interfering BS needs CSI to implement the precoding. Assuming that the CSI of the $k$th link is available at the corresponding interfering BS, the precoding matrix $W_k$ is obtained through singular value decomposition (SVD) of the channel matrix from the $k$th BS to the $k$th mobile. The equivalent channel vectors can be written as

$$
\begin{bmatrix}
\tilde{h}_{k,i1} \\
\tilde{h}_{k,i2}
\end{bmatrix} = \begin{bmatrix}
w_{k,11} & w_{k,11} \\
w_{k,21} & w_{k,21}
\end{bmatrix} \begin{bmatrix} h_{k,i1} \\
h_{k,i2}
\end{bmatrix} = \begin{bmatrix} w_{k,1}h_{k,i} \\
w_{k,2}h_{k,i}
\end{bmatrix},
$$

(2.5)

where $w_{k,i} = [w_{k,i1} \ w_{k,i2}]$, $h_{k,i} = [h_{k,i1} \ h_{k,i2}]^T$ and $i = 1, 2$. Because $W_k$ is a unitary matrix, the $\tilde{h}_{k,ij}$ ($i = 1, 2; j = 1, 2$) are still i.i.d. complex Gaussian random variables with zero mean and unit variance. This means the average interfering power is the same as when OLSM is used in the interfering links. So, the distribution of the SIR for CLSM also has the same form as (2.3).

### 2.1.2.2 Second Category Interferers

When MBF or MRT is used by the interfering BSs, two transmit antennas are used to send the same symbol during one symbol period. Hence, the coding matrix of the $k$th BS in (2.1) is $\begin{bmatrix} s_{k,1} & s_{k,1} \\
 s_{k,2} & s_{k,2}\end{bmatrix}$. In the case of MBF, the precoding matrix $W_k$ is given by

$$
W_{k,MBF} = \begin{bmatrix} \sqrt{2}v_{k,1} & 0 \\
 0 & \sqrt{2}v_{k,2}\end{bmatrix},
$$

(2.6)

with $|v_{k,1}|^2 + |v_{k,2}|^2 = 1$, where $v_{k,1}$ and $v_{k,2}$ come from the singular vector $\begin{bmatrix} v_{k,1} \\
 v_{k,2}\end{bmatrix}$ corresponding to the maximum singular value of the channel matrix from the $k$th
BS to the \( k \)th mobile. In the case of MRT, the precoding matrix \( \mathbf{W}_k \) is given by

\[
\mathbf{W}_{k,MRT} = \begin{bmatrix}
\sqrt{2}g_{k,1}/\sqrt{|g_{k,1}|^2 + |g_{k,2}|^2} & 0 \\
0 & \sqrt{2}g_{k,2}/\sqrt{|g_{k,1}|^2 + |g_{k,2}|^2}
\end{bmatrix},
\]

(2.7)

where \( g_{k,1} \) and \( g_{k,2} \) are the channel gains from the first and second transmit antennas in the \( k \)th BS to the \( k \)th mobile, respectively. (Note that only one antenna is used in the \( k \)th receiver when MRT is adopted.) Obviously, (2.6) and (2.7) have the same function when they act as the precoding matrix. Hence, MBF and MRT have the same performance when they are used in the interfering BSs. Using the notation in (2.6), after STBC decoding and MRC, by implementing some manipulations and approximations, the following SIR expression is obtained

\[
\gamma_{STBC-MBF/MRT} = \eta \cdot \frac{x_0}{\sum_{k=1}^{K} y_k + y_k},
\]

(2.8)

where \( x_0 = |h_{0,11}|^2 + |h_{0,12}|^2 + |h_{0,21}|^2 + |h_{0,22}|^2 \) has a chi-square distribution and \( y_k = \frac{|h_{0,11}h_{k,1} + h_{0,21}h_{k,2}|^2}{|h_{0,11}|^2 + |h_{0,21}|^2} \) follows an exponential distribution. Hence, the pdf expression of SIR for a general \((NTx, MRx)\) antenna configuration is

\[
f_{\gamma}(\gamma) \approx \frac{N}{\eta} \cdot \frac{\Gamma(NM + K)(N\gamma/\eta)^{NM-1}}{\Gamma(NM)\Gamma(K)(1 + N\gamma/\eta)^{NM+K}},
\]

(2.9)

where \( \gamma \geq 0 \).

Based on the results summarized above, it is shown in [18] that the five MIMO co-channel modes can be divided into two categories: the first category includes STBC, OLSM and CLSM; the second MBF and MRT. Each chi-square variable with degree of freedom 2 can be seen as an independent signal component. By observing (2.8) and (2.2), it can be seen that there are two independent interfering signals (from each BS) and two identical interfering signals (from each BS) for the first and second categories, respectively. Intuitively, the second category, in which a single data stream is transmitted, would have less impact on the desired link. With
STBC used in the desired link, the \textit{pdf}s of the SIRs can be combined as (2.10) when the interfering BSs adopt the \textit{p}th \((p = 1, 2)\) category MIMO schemes.

\[
f_\gamma(\gamma) = \frac{N}{N^{2-p}\eta} \cdot \frac{\Gamma(NM + N^{2-p}K)(N\gamma/N^{2-p}\eta)^{NM-1}}{\Gamma(NM)\Gamma(N^{2-p}K)(1 + N\gamma/N^{2-p}\eta)^{NM+N^{2-p}K}}. \tag{2.10}
\]

It is shown in [18] that the analytic results match well with simulation.

\subsection*{2.2 A Scheduling Algorithm}

In a multi-user cellular system, there are several interfering co-channel cells surrounding a desired cell, so the desired receiver will also receive interference from other BSs. From the results in [18], we can see that the specific transmission mode used by the interferers is not the key point when investigating the impact of the interferers on the desired link. In this section, we mainly explore an algorithm that schedules transmissions without knowledge of the interference. Our motivation is to devise a robust scheduling algorithm that can achieve good performance in this uncertain interference environment.

Assume some MIMO mode is adopted in both the desired and interfering BSs, and that signals are transmitted in packets (each packet having length \(L\)). The SIR during the previous packet transmission can be measured and will be used to determine the transmission rate of the current packet. Since the current interference is unknown, the SIR of the current packet is also unknown and random. What we need to figure out is how to utilize the previous SIR to predict the current SIR and achieve the satisfactory performance.

In order to utilize the previous SIR to determine the current transmission rate, here, we introduce a margin denoted as \(\delta\). We use index \(n-1\) and \(n\) to designate the previous and current packet, respectively, and then we decide the number of bits per symbol in the current packet as \(k_n = \log_2(1 + \gamma_{n-1}/\delta)\). So the margin \(\delta\) is a backoff of the achievable rate in the previous packet transmission.
We assume M-QAM signals are transmitted and we use the average throughput to evaluate the system performance. Specifically, we define throughput as

\[ TP = \log_2 M (1 - \text{BLER}) = \log_2 M (1 - \text{SER})^L, \quad (2.11) \]

where \( \log_2 M = k \), \( \text{BLER} \) is the packet error rate, and \( \text{SER} \) is the symbol error rate. For M-QAM signals, \( 1 - \text{SER} = (1 - P \sqrt{M})^2 = \left[ 1 - 2 \left( 1 - \frac{1}{\sqrt{M}} \right) Q \left( \sqrt{\frac{3 \gamma_n}{M-1}} \right) \right]^2 \) [34]. So

\[ TP = \log_2 (1 + \frac{\gamma_n - 1}{\delta}) \left[ 1 - 2 \left( 1 - \frac{1}{\sqrt{1 + \frac{\gamma_n - 1}{\delta}}} \right) Q \left( \sqrt{\frac{3 \delta \gamma_n}{\gamma_n - 1}} \right) \right]^{2L}. \quad (2.12) \]

To evaluate the average throughput, we need to average \( TP_n \) over \( \gamma_n - 1 \) and \( \gamma_n \).

We assume the interference is unknown, and consider two cases: the interference link is random and the interference link is constant.

### 2.2.1 Random Interference

Assume STBC is adopted in both the desired and interfering BSs. Using the results in [18], the distribution of the SIR for a general \((NT_x, MR_x)\) antenna configuration is given by (2.3). Since it is difficult to obtain the joint distribution of \( \gamma_n - 1 \) and \( \gamma_n \) when they are partially correlated, here, we consider two extreme cases: completely correlated and completely uncorrelated.

For convenience, we define the margin in dB as \( \Delta \), so \( \Delta = 10 \log_{10} \delta \). We need to determine the margin required to achieve a guaranteed level of performance.

**Correlated:** In this case, the SIRs in the previous and current packets are totally correlated, and \( \gamma_n = \gamma_n - 1 = \gamma \). So, we have

\[ TP = \log_2 (1 + \frac{\gamma}{\delta}) \left[ 1 - 2 \left( 1 - \frac{1}{\sqrt{1 + \gamma / \delta}} \right) Q \left( \sqrt{3 \delta} \right) \right]^{2L}, \quad (2.13) \]

and the average throughput can be written as

\[ E(TP) = \int_{0}^{+\infty} f(\gamma) \log_2 (1 + \frac{\gamma}{\delta}) \left[ 1 - 2 \left( 1 - \frac{1}{\sqrt{1 + \gamma / \delta}} \right) Q \left( \sqrt{3 \delta} \right) \right]^{2L} d\gamma. \quad (2.14) \]
Uncorrelated: In this case, the SIRs in the previous and current packets are totally uncorrelated (i.e., $E[\gamma_n\gamma_{n-1}] = 0$). So, the average throughput can be written as

$$E(TP) = \int_{0}^{+\infty} f(\gamma_{n-1}) \int_{0}^{+\infty} f(\gamma_n) \log_2(1 + \gamma_{n-1}/\delta) \cdot \left[ 1 - 2 \left( 1 - \frac{1}{\sqrt{1 + \gamma_{n-1}/\delta}} \right) Q \left( \sqrt{\frac{3\delta\gamma_n}{\gamma_{n-1}}} \right) \right]^{2L} d\gamma_n d\gamma_{n-1}. \quad (2.15)$$

2.2.2 Constant Interference

Assume the interference power is constant, then we can show that the SIR has the following pdf

$$f(\gamma) = \frac{1}{\eta \Gamma(MN)} \left( \frac{\gamma}{\eta} \right)^{MN-1} \exp \left( -\frac{\gamma}{\eta} \right). \quad (2.16)$$

Correlated: In this case, the SIRs in the previous and current packets are totally correlated, and $\gamma_n = \gamma_{n-1} = \gamma$. So,

$$TP = \log_2(1 + \gamma/\delta) \left[ 1 - 2 \left( 1 - \frac{1}{\sqrt{1 + \gamma/\delta}} \right) Q \left( \sqrt{3\delta} \right) \right]^{2L}, \quad (2.17)$$

and the average throughput is

$$E(TP) = \int_{0}^{+\infty} f(\gamma) \log_2(1 + \gamma/\delta) \left[ 1 - 2 \left( 1 - \frac{1}{\sqrt{1 + \gamma/\delta}} \right) Q \left( \sqrt{3\delta} \right) \right]^{2L} d\gamma. \quad (2.18)$$

Uncorrelated: In this case, the SIRs in the previous and current packets are totally uncorrelated. So, the average throughput is

$$E(TP) = \int_{0}^{+\infty} f(\gamma_{n-1}) \int_{0}^{+\infty} f(\gamma_n) \log_2(1 + \gamma_{n-1}/\delta) \cdot \left[ 1 - 2 \left( 1 - \frac{1}{\sqrt{1 + \gamma_{n-1}/\delta}} \right) Q \left( \sqrt{\frac{3\delta\gamma_n}{\gamma_{n-1}}} \right) \right]^{2L} d\gamma_n d\gamma_{n-1}. \quad (2.19)$$

2.2.3 Simulation Results

In this section, we compute the average throughput for the different cases as a function of the margin.
Figure 2.2: Average throughput with a totally \textbf{correlated} fading on the desired link and \textbf{random} interference links. $P_0/P_I = 1$, $M = N = 2$.

Figure 2.3: Average throughput with a totally \textbf{correlated} fading on the desired link and \textbf{random} interference links. $P_0/P_I = K$, $M = N = 2$. 
Figure 2.4: Average throughput with a totally uncorrelated fading on the desired link and random interference links. $P_0/P_I = 1$, $M = N = 2$.

Figure 2.5: Average throughput with a totally uncorrelated fading on the desired link and random interference links. $P_0/P_I = K$, $M = N = 2$. 
Figs. 2.2 and 2.3 show the performance of the algorithm with the fading on the desired link completely correlated from one packet to another, and interference links random. In Fig. 2.2, the transmit power of all the BSs is assumed to be equal, i.e., $P_0/P_I = 1$. The length of the packet $L$ is assumed to be 500 symbols. We can see that the average throughput is reduced as the number of interferers $K$ increases, as expected, since the interference power is increased. In Fig. 2.3, $P_0/P_I = K$, where $K$ is the number of the interferers, thus the total transmit power of each of the interfering BSs is assumed to be equal to the transmit power of the desired link. Clearly then, as expected, the average throughput is almost the same with different numbers of interferers, since the total interference power is the same. Figs. 2.4 and 2.5 show the performance of the algorithm with fading on the desired link completely uncorrelated from packet to packet, and interference links random. We see a similar variation with $K$ as in Figs. 2.2 and 2.3. We also see that the average throughput is lower (and really unusable) when the channel conditions are uncorrelated from packet to packet.

Figs. 2.6 and 2.7 show the average throughput assuming the interference is constant from packet to packet, and the fading on the desired link is completely correlated and uncorrelated, respectively. We can see that the performance is improved as the number of antennas increases. Compared with random interference, the average throughput is higher when the interference is constant, because the SIR only depends on the desired link, and the variation in SIR is smaller. Thus the SIR is easier to estimate. Besides, the throughput is reduced when the channel correlation decreases, because it is more difficult to estimate the SIR when the correlation in the fading is small on the desired link from one packet to another. The margin $\Delta$ can be chosen to maximize the average throughput.

Fig. 2.8 shows the throughput with different modulation sizes as a function of the measured SIR when the fading on the desired channel is totally correlated.
between the two packets. From the figure, we can easily see that there is an optimum number of bits per symbol at each value of SIR; obviously, ideally, the chosen modulation should follow the envelope of the curves.

When $\rho = 0$, SIR is totally uncorrelated from one packet to the next. So, even though the interference is known and constant, the only change is in the distribution of the SIR. Fig. 2.9 shows the performance with different modulation sizes as a function of the measured SIR when the fading on the desired channel is totally uncorrelated from packet to packet. We can see that if we change the margin according to the measured SIR of the previous packet, we can get a constant average throughput.

In partially correlated cases, since it is difficult to get the theoretical formula of the distribution of SIR, here Monte-Carlo simulations are used to get the average throughput. For simplicity, we set $M = N = 1$, and assume the interference is constant. Fig. 2.10 shows how the maximum average throughput changes with different values of the channel correlation coefficient $\rho$ as we vary the margin. Since there are only single antennas at the transmitter and receiver, the throughput is lower than for the $2 \times 2$ case. As expected, the achievable average throughput increases as $\rho$ increases. For a fixed margin $\Delta$, the average throughput initially increases and then is reduced as the measured SIR increases; this is because, when the measured SIR is small, the algorithm is too conservative to provide good performance, and when the measured SIR is large, the given margin might be not large enough. As the measured SIR increases, the optimum value for the margin $\Delta$ increases because the probability that the SIR in the next packet transmission is as good as the SIR in the current packet gets smaller. By choosing the margin properly, based on the measured SIR, we can improve the performance significantly.
Figure 2.6: Average throughput with a totally correlated fading on the desired link and constant interference, $P_0/P_I = 1$. 

(a) $M = 2$, $\rho = 1$

(b) $N = 2$, $\rho = 1$
Figure 2.7: Average throughput with a totally **uncorrelated** fading on the desired link and **constant** interference, $P_0/P_I = 1$. 
Figure 2.8: Average throughput with different modulation sizes under different measured SIR when the fading on the desired channel is totally correlated from packet to packet.

Figure 2.9: Average throughput with different modulation sizes under different measured SIR when the fading on the desired channel is totally uncorrelated from packet to packet.
\( \rho = 0 \)

\( \rho = 0.5 \)

(a) \( \rho = 0 \)

(b) \( \rho = 0.5 \)
Figure 2.10: Average throughput using different margin value $\Delta$ with different values of channel correlation coefficient $\rho$, $M = N = 1$. 
Chapter 3

MITIGATING INTER-TIER INTERFERENCE IN FEMTOCELLULAR SYSTEMS

One way to increase the capacity of a wireless system is by placing the transmitter and receiver closer to each other to reduce the path loss [35]. This can be accomplished by introducing tiers into the existing cellular system, typically in the form of microcells, hotspots, etc. Another less expensive alternative is the femtocell. Femtocells are low-power base stations purchased and installed by users to get better indoor coverage. The main potential advantages of femtocells include better coverage and capacity, improved macrocell reliability, cost benefits, and reduced subscriber turnover [19].

3.1 Femtocell Architecture

Fig. 3.1 shows a typical femtocellular system with multiple macrocells and several femtocells in each macrocell. The large hexagons represent the macrocellular coverage area, and the small circles represent the coverage areas of the individual femtocells. All of the FBSs are connected to the local ISP networks to reduce the cost of the backbone installation. We assume that each femtocell can communicate with the macrocellular operators through the backbone network.

3.2 Technical Challenges

Although femtocells have several potential advantages, in order for femtocells to provide significant capacity and coverage gains, several technical challenges need to be addressed [20].
In a two-tier cellular system, where the FBSs work on the same frequency band as the MBSs, co-channel interference becomes an important factor that limits the overall system performance. Although the transmit power of the FBSs is low and the path loss from the indoor to the outdoor systems helps to alleviate the interference, as the number of femtocells increases, the cumulated interference becomes a serious issue. Thus, power control at the FBSs is at least required to avoid performance degradation. Besides, further interference mitigation strategies are also required. In order to apply these interference mitigation strategies, good synchronization is very important, as well as efficient exchange of messages between the femtocells and macrocells. In addition, security and self-organization are also technical challenges for femtocells. In this thesis, we mainly consider the interference management in femtocellular systems.
3.3 Radio Environment

In the two-tier femtocellular systems, the signals are transmitted from the transmitter to the receiver through wireless channels. In this section, we briefly review the major characteristics of the wireless channel. Note that the characteristics of wireless channels are not limited to these, but we only consider these factors in this thesis.

3.3.1 Path Loss

Path loss is caused by dissipation of the power radiated by the transmitter as well as by effects of the propagation channel. The received power variation due to path loss occurs over long distances (100-1000 m), therefore it is sometimes referred to as large-scale propagation effect. In the following, we will introduce three path-loss models for femtocellular systems [38]-[39]: outdoor-to-outdoor (indoor), indoor-to-outdoor, and indoor-to-indoor.

3.3.1.1 Outdoor-to-Outdoor (Indoor) Path-Loss Model

This path-loss model can be applied to transmission from outdoor to outdoor, or outdoor to indoor users. Thus, we can use it to model the path loss between the MBSs and the MUEs (outdoor-to-outdoor) or the MBSs and the FUEs (outdoor-to-indoor). For the outdoor-to-indoor case, the additional loss is around 12 dB for transmission through a heavy wall and 5 dB for a light wall. The assumptions and conditions of this path-loss model include high BS transmit power and a non-line-of-sight (NLOS) environment. The path loss is modeled as:

$$PL(dB) = 40(1 - 4 \times 10^{-3} \Delta h_b) \log_{10} d - 18 \log_{10} \Delta h_b + 21 \log_{10} f_c + 80,$$

(3.1)

where $d$ is the distance between the transmitter and receiver in km, $f_c$ is the carrier frequency in MHz, and $\Delta h_b$ is the antenna height in meters measured from the average rooftop level.
### 3.3.1.2 Indoor-to-Outdoor Path-Loss Model

This model can be applied to wireless transmission from indoor to outdoor users. So we can use it to model the path loss between the FBSs and the MUEs or the FUEs in the other femtocells. This model is expressed as

\[
PL(dB) = PL_b + PL_{tw} + PL_{in}.
\]  

(3.2)

\(PL_b\), the path loss in dB between the FBS and the outdoor macrocellular user, is given as

\[
PL_b = max(PL_{B1}, PL_{free}),
\]

(3.3)

and

\[
PL_{B1} = 41 + 20 \log_{10}(f_c/5) + 22.7 \log_{10}(d_{out} + d_{in})
\]

(3.4)

\(PL_{B1}\) is the urban microcell path loss in dB, \(PL_{free}\) is the free-space path loss in dB, \(f_c\) is the carrier frequency in GHz, \(d\) is the distance between the transmitter and the receiver, \(d_{out}\) is the distance between the receiver and the wall, and \(d_{in}\) is the distance between the transmitter and the nearest wall.

\(PL_{tw}\), the exterior wall penetration loss in dB, is given as

\[
PL_{tw} = 14 + 15(1 - \cos\theta)^2,
\]

where \(\theta\) is the angle between the outdoor path and the wall. \(PL_{in}\), the path loss from the FBS to the nearest wall, is given by

\[
PL_{in} = 0.5d_{in}.
\]

### 3.3.1.3 Indoor-to-Indoor Path-Loss Model

This model is applied to the channels between the FBSs and the FUEs in the same femtocells, and can be expressed as

\[
PL(dB) = 37 + 30 \log_{10} d + 18.3n \frac{n+2}{n+1} - 0.46,
\]

(3.5)

where \(n\) is the number of floors in the path between the transmitter and the receiver.
3.3.2 Shadow Fading

Shadow fading is caused by obstacles between the transmitter and receiver that attenuate the signal power through absorption, reflection, scattering, and diffraction. The receiver power variation due to shadowing occurs over distances that are proportional to the length of the obstructing object (10-100 m in outdoor environments and less in indoor environments), and this variation is often referred to as large-scale fading [37].

Since the location, size, and other properties of the blocking objects are generally unknown, statistical models must be used to characterize this phenomenon. The most common model for shadow fading is to represent the signal variation with a Gaussian distribution when the signal power is considered in dB, we call this log-normal shadowing. This model has been empirically confirmed to model the shadow fading accurately in both outdoor and indoor environments.

In the log-normal shadowing model, the ratio of transmit-to-receive power \( \psi = P_t/P_r \) is assumed to be random with a log-normal distribution. If this ratio is represented in dB, it can be described by a Gaussian distribution [37]

\[
 f(\psi_{dB}) = \frac{1}{\sqrt{2\pi \sigma^2_{\psi_{dB}}}} \exp \left[ -\frac{(\psi_{dB} - \mu_{\psi_{dB}})^2}{2\sigma^2_{\psi_{dB}}} \right], \tag{3.6}
\]

where \( \mu_{\psi_{dB}} \) is the mean of \( \psi_{dB} = 10 \log_{10} \psi \) in dB, and \( \sigma^2_{\psi_{dB}} \) is the standard deviation of \( \psi_{dB} \) (also in dB). The mean can be based on an analytical model or empirical measurements.

Combining the shadow fading with path loss, the ratio of the received to transmitted power in dB is given by [37]

\[
 \frac{P_r}{P_t}(dB) = 10 \log_{10} K - 10a \log_{10} \frac{d}{d_0} - \psi_{dB}, \tag{3.7}
\]

where \( \psi_{dB} \) is a Gaussian-distributed random variable with mean 0 and variance \( \sigma^2_{\psi_{dB}} \), \( K \) is a unitless constant that depends on the antenna characteristics and the
average channel attenuation, \( d_0 \) is a reference distance for the antenna far field, \( d \) is the distance between the transmitter and the receiver, and \( a \) is the path-loss exponent.

### 3.3.3 Multipath Fading

In wireless systems, the transmitted signal is reflected by objects located between the transmitter and receiver. Each of these “echoes” has a different amplitude, phase, and time of arrival. These signals might constructively or destructively interfere at the receiver. The resulting effect is called multipath fading. These variations in the received power occur over very short distances, on the order of the signal wavelength, and so are sometimes referred to as small-scale fading [37]. When the number of paths is large and there is no line-of-sight component, the amplitude of the received signal follows a Rayleigh distribution

\[
p(r) = \frac{r}{\sigma^2} e^{x} \left\{ -\frac{r^2}{2\sigma^2} \right\},
\]

where \( r \) is the envelope of the received signal, and \( 2\sigma^2 \) is the mean power of the multipath signal.
Chapter 4

BEAMFORMING WITH NULLING FOR INTERFERENCE MITIGATION IN FEMTOCELLULAR SYSTEMS

As stated in the last chapter, femtocells are becoming increasingly attractive to cellular operators because of their potential for better coverage and capacity [19]-[20]. A series of technical challenges must be overcome, however, before femtocells can be widely deployed including resource allocation, interference management, and synchronization [19]-[36]. Here, we focus on interference mitigation. The introduction of another tier into the existing cellular system creates interference. Although the typical transmit power of FBSs is low, as the number of femtocells within a macrocell increases, the cumulative interference from the FBSs to the MUEs could cause significant degradation of the macrocellular performance. Here, we consider beamforming (BF) with nulling technique to mitigate the interference from the FBSs to the MUEs.

Beamforming (BF) is a multiple-antenna technique that can provide significant gains to users [37]. With proper weighting of the signals to and from these multiple antennas, the transmitter can maximize the signal power at the desired receiver (transmit beamforming), and minimize its interference to users served by another cell (BF with nulling) [40]. Therefore, beamforming with nulling can be an effective method for interference management, since it advantageously attenuates interfering signals while boosting power to desired user devices. As a result, the signal-to-interference-plus-noise ratio (SINR) is improved for communications with user devices.
Beamforming with nulling is introduced in Section 4.1. Its application to femtocellular systems is described in Section 4.2, and simulation results are presented in Section 4.3.

4.1 Beamforming (BF) with Nulling

As shown in Fig. 4.1, for a MIMO system with $N_t$ transmit and $N_r$ receive antennas, we model the received signal as [37]

$$Y = \sqrt{P}u^H H Q X + u^H n,$$  \hspace{1cm} (4.1)$$

where $P$ is the average received power (including path loss), $H$ is the $N_r \times N_t$ channel matrix, $X$ is the $N_s \times 1$ transmitted signal vector ($N_s$ is the number of signal streams), $n$ is an additive white Gaussian noise vector, $Q$ is a normalized $N_t \times N_s$ precoding matrix, and $u$ is a normalized receiver shaping matrix. The channel coefficients are modeled as i.i.d. complex Gaussian random variables with zero mean and unit variance (representing a Rayleigh fading signal).
4.1.1 Transmit Beamforming (TX BF)

Consider a MIMO channel with the $N_r \times N_t$ channel matrix $H$ known to both the transmitter and the receiver. For any matrix $H$, we can obtain its singular value decomposition (SVD) as

$$H = U \Sigma V^H,$$  \hspace{1cm} (4.2)

where the $N_r \times N_r$ matrix $U$ and the $N_t \times N_t$ matrix $V$ are unitary matrices and $\Sigma$ is an $N_r \times N_t$ diagonal matrix of singular values $\{\sqrt{\lambda_i}\}$ of $H$, where $\lambda_i$ is the $i$th largest eigenvalue of $HH^H$.

In this thesis, we assume $N_s = 1$, that is, a single stream is transmitted; thus, $Q$ and $u$ are both vectors. This scheme is also referred to as MIMO beamforming. So, in Fig. 4.1, $x_1 = x_2 = \ldots = x_{N_t}$. The received signal-to-noise ratio (SNR) can be maximized by choosing $u$ and $Q$ as the principal left and right singular vectors of the channel matrix $H$. That is, for the maximum singular value of $H$, $u$ and $Q$ are respectively the first columns of $U$ and $V$. And the corresponding received SNR is $\lambda_{max} \rho$, where $\lambda_{max}$ is the largest eigenvalue of $H$, and where $\rho$ is the average SNR.

4.1.2 BF with Nulling for Cell-Edge Users

As illustrated in Fig. 4.2, cell-edge users can experience lower throughputs due to the smaller signal power from the serving BS and the larger interference power from the interfering BS. Beamforming with nulling technique [41] can be applied to increase the SINR at the cell-edge users. By simultaneously beamforming at the desired user and nulling at the undesired user, beamforming with nulling can improve the signal power at the desired user, avoid severe interference at the undesired user, and therefore, improve the SINRs at both the desired and undesired users.

We assume all BSs are connected to each other via a backhaul network. Each MS measures the channels from the serving BS and the interfering BSs. These measurements are sent to the BSs. Consider a cellular system with $K$ co-channel
Figure 4.2: Beamforming with nulling for cell-edge users in single-tier cellular systems.

BSs. As discussed above, BF with nulling increases the average signal power to the desired user and reduces the average interference power received by the co-channel users. The BF with nulling precoder at the $k$th BS is calculated as

$$Q_k = \max_{Q_k} \frac{PQ_k^H H_k^H H_k Q_k}{PQ_k^H \left( \sum_{i=1, i \neq k}^{K} H_i^H H_i \right) Q_k + N_0}, \quad (4.3)$$

where $P$ is the transmit power of the BSs, $N_0$ is the noise power at the receiver, $H_k$ is the desired link from the $k$th BS to the $k$th user, $H_i$ is the interference link from the $k$th BS to the $i$th user, and $Q_k$ is the precoder for the $k$th BS. The solution to this optimization problem, $Q_n$, is the eigenvector corresponding to the largest
eigenvalue of the matrix

\[ A = \left( \sum_{i=1, i \neq k}^{K} H_i^H H_i + \frac{N_0}{P} I \right)^{-1} H_k^H H_k, \]  

(4.4)

where \( I \) denotes an identity matrix.

### 4.2 Application of Beamforming with Nulling in Femtocellular Systems

As stated in Chapter 3, interference management is one of the most important challenges for introducing femtocells into existing cellular systems. Beamforming with nulling has been shown to mitigate inter-cell, same-tier, interference [40]. Therefore, this technique can also be applied in two-tier femtocellular systems to alleviate the cross-tier interference. Fig. 4.3 shows how beamforming with nulling can be applied at the FBSs to place a null at the macrocellular user equipment (MUE) and mitigate co-channel interference at the MUE from the FBSs. Since BF with nulling at the FBSs can increase the signal power at the desired FUE and reduce the interference power at the MUE, this technique can improve both macrocellular and femtocellular performance in a femtocellular system.

Analogous to (4.4), with beamforming at the desired FUE and nulling at the MUE, the precoder at the FBS, \( Q_F \), is the eigenvector corresponding to the largest eigenvalue of the matrix

\[ A = \left( H_{F,m}^H H_{F,m} + \frac{N_0}{P} I \right)^{-1} H_{F,f}^H H_{F,f}, \]  

(4.5)

where \( H_{F,f} \) is the desired channel from the FBS to its desired FUE, \( H_{F,m} \) is the interference channel from the FBS to the MUE, and \( P \) is the received power at the MUE from the FBS.

Consider a femtocellular system with \( N_M \) macrocells and \( N_F \) femtocells sharing the same frequency. Assume there is one active UE in each cell. Denote the channel between the \( i \)th MBS/FBS and the \( j \)th MUE/FUE as \( H_{(M/F),i,(m/f),j} \), and the average received power at the \( j \)th MUE/FUE from the \( i \)th MBS/FBS as \( P_{(M/F),i,(m/f),j} \).
Figure 4.3: Beamforming with nulling in femtocellular systems.

Then, the SINR at the MUE in macrocell $i = 1$ is

$$SINR_{MUE} = \frac{P_{M_1,m_1} \| H_{M_1,m_1} Q_{M_1} \|^2}{\sum_{i=2}^{N_M} P_{M_i,m_1} \| H_{M_i,m_1} Q_{M_i} \|^2 + \sum_{j=1}^{N_F} P_{F_j,m_1} \| H_{F_j,m_1} Q_{F_j} \|^2 + P_{n_m}},$$

(4.6)

and the SINR at the FUE in femtocell $i = 1$ is

$$SINR_{FUE} = \frac{P_{F_1,f_1} \| H_{F_1,f_1} Q_{F_1} \|^2}{\sum_{i=1}^{N_M} P_{M_i,f_1} \| H_{M_i,f_1} Q_{M_i} \|^2 + \sum_{j=2}^{N_F} P_{F_j,f_1} \| H_{F_j,f_1} Q_{F_j} \|^2 + P_{n_f}},$$

(4.7)

where $Q_{M_j}$ and $Q_{F_j}$ are the precoders at the $j$th MBS and FBS, and $P_{n_m}$ and $P_{n_f}$ are the noise powers at the MUE and FUE, respectively.

4.3 Performance Analysis of Beamforming with Nulling in Femtocellular Systems

In this section, we provide simulation results of macrocellular (microcellular) and femtocellular performance with beamforming with nulling applied at the FBSs.
in both macrocellular and microcellular environments. The differences between the macrocellular and microcellular environments include coverage ranges, transmit powers of the BSs, the heights of the transmit antennas, and so on.

### 4.3.1 Macrocellular Environment

Initially, assume that there is only one active FUE at each time instant and the MBS employs either no BF or TX BF. Path-loss models follow those in Chapter 3, and the key parameters are given in Table 4.1. We assume the femtocells are uniformly distributed in the macrocell, and each UE is also uniformly distributed inside the coverage area of its serving BS.

**Table 4.1: Simulation Parameters for the Macrocellular Environment**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of transmitting antennas $N_t$</td>
<td>4</td>
</tr>
<tr>
<td>Number of receiving antennas $N_r$</td>
<td>1</td>
</tr>
<tr>
<td>Carrier frequency $f_c$</td>
<td>2.5 GHz</td>
</tr>
<tr>
<td>Macro BS antenna height above mean rooftop level $\Delta h_{BS}$</td>
<td>20 m</td>
</tr>
<tr>
<td>Macro BS transmit power</td>
<td>46 dBm</td>
</tr>
<tr>
<td>Noise power at UE</td>
<td>-100 dBm</td>
</tr>
<tr>
<td>Macrocell radius</td>
<td>1000 m</td>
</tr>
<tr>
<td>Femtocell radius</td>
<td>10 m</td>
</tr>
</tbody>
</table>

### 4.3.1.1 Macrocellular Downlink Throughput

In this section, we present the macrocellular downlink performance when beamforming with nulling is applied at the FBSs.

- **Single-cell performance**

  In Fig. 4.4, we show the downlink (DL) performance for a macrocell in a single-cell environment with different transmission modes applied at the MBS and FBSs. Specifically, the performance, measured as the 50th percentile of the CDF of the throughput, is shown as a function of the number of femtocells within
Figure 4.4: 50% macrocellular DL throughput in a single macrocell environment as a function of the number of femtocells. FBS transmit power is 20 dBm.

a given macrocell. The transmit power of the FBSs is 20 dBm. As expected, TX BF at the MBS provides much better performance because it maximizes the signal power at the MUE. The use of TX BF at the FBSs does not improve the downlink throughput at the macrocell because this technique does not consider the interference generated at the MUE. As the number of femtocells increases, the interference at the MUE increases, and the macrocellular performance degrades rapidly with no BF or TX BF applied at the FBSs. When BF with nulling is applied at the FBSs, the performance is significantly improved. For TDD systems, using an uplink sounding mechanism, each FBS can effectively place a null in the direction of the MUE. As such, the degradation in the macrocellular DL throughput as the number of femtocells increases can be minimized.

- Multi-cell performance

In Fig. 4.5, we show the 50% macrocellular DL throughput in the presence of multiple macrocells with the FBS transmit power set to 20 dBm. A seven-hexagon
Figure 4.5: 50% macrocellular DL throughput in a multiple macrocell environment as a function of the number of femtocells. FBS transmit power is 20 dBm.

multicell layout is used. As expected, the baseline throughput is dramatically lower because of the interference from co-channel cells. (Note that we assume a worst-case scenario where the same channel is used in every adjacent cell.) Notice, however, that using BF with nulling at the FBSs still provides significant improvement.

• Impact of FBS transmit power

In Fig. 4.6, the 50% macrocellular DL throughput with the FBS transmit power reduced to 10 dBm is given in both single and multiple macrocell environments. Since the interference power from the FBSs is lower, the macrocellular performance is generally better, especially when no BF or TX BF is applied at the FBSs. BF with nulling still works much better than no BF and TX BF in the single macrocell case. When there are multiple macrocells, the main source of interference at the MUE is the interfering MBSs, and the degradation of the macrocellular performance with an increase in the number of femtocells is not obvious even when no
BF or TX BF is used. Therefore, there is not much performance improvement using BF with nulling.

4.3.1.2 Femtocellular Downlink Throughput

In this section, we present the femtocellular downlink performance in a macrocellular environment when beamforming with nulling is applied at the FBSs.

- Single-cell and multi-cell performance

The use of BF with nulling at the FBSs will result in some degradation in the femtocellular DL throughput because the transmit beamforming gain is sacrificed to place nulls in the direction of the MUE. This is shown in Figs. 4.7 and 4.8 for the single-cell and multi-cell cases; the penalty, however, is not significant. Also, there will be additional interference to an FUE caused by other FBSs. We also show that there is no benefit in doing additional nulling at one or two FUEs in the same macrocell. Comparing Figs. 4.7 and 4.8, the femtocellular throughput in a
Figure 4.7: 50% femtocellular DL throughput as a function of the number of femtocells in single macrocell environment. FBS transmit power is 20 dBm.

multi-cell environment is a little lower than that in the single-cell case, because the interference to an FUE from other MBSs and FBSs is higher in the multi-cell case. However, due to the lower transmit power of the FBSs and the greater distance between an FUE and interfering MBSs, the femtocellular performance difference between the single-cell and multi-cell environments is small. In addition, because the transmit power of the FBSs is lower, the femtocellular throughput is much lower than the macrocellular throughput.

• Impact of FBS transmit power

In Fig. 4.9, we show the 50% femtocellular DL throughput in a single-macrocell environment with the FBS transmit power reduced to 10 dBm. Since the transmit power of the FBS is reduced, the interference at the FUE is mainly from the MBSs, which does not vary with an increase in the number of femtocells in each macrocell. Therefore, the femtocellular performance does not degrade much
Figure 4.8: 50% femtocellular DL throughput as a function of the number of femtocells in multiple macrocell environment. FBS transmit power is 20 dBm.

as the number of femtocells increases. Also, as one should expect, the femtocellular throughput with 10-dBm FBS transmit power is lower than that with 20-dBm FBS transmit power.

4.3.2 Microcellular Environment

In a microcellular environment, as in the previous section, we assume that there is only one active FUE at each time instant and the microcellular base station (mBS) uses either no BF or TX BF. Path-loss models follow those in Chapter 3, and the key parameters are given in Table 4.2. Note that the mBS transmit power and the microcell radius are different from those in the macrocellular environment. The outdoor-to-outdoor and outdoor-to-indoor path-loss models for microcells are also different from those used for the macrocells. Generally, the outdoor-to-outdoor and outdoor-to-indoor path loss in a microcellular environment are higher than those in the macrocellular environment because the antenna height of a mBS is much lower
Figure 4.9: 50% femtocellular DL throughput in a single macrocell environment as a function of the number of femtocells. FBS transmit power is 10 dBm.

than a MBS. As previously assumed, the femtocells are uniformly distributed in the microcell and each UE is also uniformly distributed inside the BS coverage area.

Table 4.2: Simulation Parameters for the Microcellular Environment

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of transmitting antennas</td>
<td>$N_t$</td>
</tr>
<tr>
<td>Number of receiving antennas</td>
<td>$N_r$</td>
</tr>
<tr>
<td>Carrier frequency $f_c$</td>
<td></td>
</tr>
<tr>
<td>Micro BS transmit power</td>
<td></td>
</tr>
<tr>
<td>Noise power at UE</td>
<td></td>
</tr>
<tr>
<td>Microcell radius</td>
<td></td>
</tr>
<tr>
<td>Femtocell radius</td>
<td></td>
</tr>
</tbody>
</table>

4.3.2.1 Microcellular Downlink Throughput

In this section, we present the microcellular downlink performance when beamforming with nulling is applied at the FBSs.
• Single-cell and multi-cell performance

![Graph showing 50% microcellular DL throughput as a function of the number of femtocells. FBS transmit power = 20 dBm.]

**Figure 4.10:** 50% microcellular DL throughput in a single microcell environment as a function of the number of femtocells. FBS transmit power = 20 dBm.

In Figs. 4.10 and 4.11, we show the downlink throughput for a microcell with 20-dBm FBS transmit power in single-cell and multi-cell environments. Due to the lower transmit power and antenna height of a mBS in the microcellular environment, the received signal power at the mUE is smaller than in the macrocellular environment, and, thus, the microcellular DL throughput is generally lower.

Because of the relatively low signal power at the micro user equipment (mUE), 20-dBm transmit power at the FBSs is obviously too high. In both the single-cell and multi-cell cases, the microcellular DL throughput deteriorates rapidly as the number of femtocells increases when no BF or TX BF is applied at the FBSs; however, BF with nulling still works much better in maintaining the microcellular performance.
Figure 4.11: 50% microcellular DL throughput in a multiple microcell environment as a function of the number of femtocells. FBS transmit power = 20 dBm.

- Impact of FBS transmit power

In Fig. 4.12, we show the 50% microcellular DL throughput in the presence of both single and multiple microcells, with the FBS transmit power reduced to 10 dBm. With no BF or TX BF, the microcellular performance still drops rapidly as the number of femtocells increases. BF with nulling also works much better than no BF or TX BF in both cases.

In Fig. 4.13, we show the 50% microcellular DL throughput in the presence of both single and multiple microcells, with the FBS transmit power reduced to 0 dBm, which is more reasonable in a microcellular environment. BF with nulling still works much better than no BF or TX BF in the single-microcell case. But, in a multiple microcell environment, BF with nulling at the FBSs does not improve the microcellular performance. Because the FBSs are assumed to place a null at the mUE in the same microcell, the interference at the mUE from the mBSs and FBSs in other microcells cannot be mitigated by BF with nulling. Thus, when the
transmit power of the FBSs is low, the benefit brought by BF with nulling is limited.

Comparing Figs. 4.10-4.13, we also notice that, with no BF and TX BF, the transmit power at the FBSs is an important factor for microcellular throughput, since the interference power at the mUE from the FBSs is proportional to the FBS transmit power. When BF with nulling is employed at the FBSs, however, the transmit power at the FBSs does not affect the microcellular performance much because the interference to the mUE from the FBSs is effectively mitigated.

- **Microcellular and macrocellular performance**

Comparing the microcellular performance with the macrocellular throughput given in Section 4.3.1, the microcellular throughput is much lower because the transmit power of the mBS is lower, the antenna height of the mBS is much lower, and the path loss from the mBS to the mUE is greater.

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**Figure 4.12:** 50% microcell DL throughput in single and multiple microcell environments as a function of the number of femtocells. FBS transmit power is 10 dBm.
Figure 4.13: 50% microcell DL throughput in single and multiple microcell environments as a function of the number of femtocells. FBS transmit power is 0 dBm.

4.3.2.2 Femtocellular Downlink Throughput

In Figs. 4.14 and 4.15, we show the 50% femtocellular DL throughput for the single-cell case with the FBS transmit power 10 dBm and 0 dBm, respectively. As stated before, BF with nulling at the FBSs will cause some femtocellular throughput degradation compared with TX BF because of the loss of beamforming gain, but the degradation is not large. When the transmit power of the FBSs is low, this degradation is even more negligible. Also, note that there is no benefit in doing additional nulling at one or two FUEs in the same microcell.

Comparing the femtocellular performance in the microcellular environment with the macrocellular case, the throughput in the microcell case is higher because the transmit power of the mBS is lower, and the path loss from the mBS to the FUE is greater due to the lower antenna height of the mBS.
Figure 4.14: 50% femtocell DL throughput in a single microcell environment as a function of the number of femtocells. FBS transmit power is 10 dBm.

Figure 4.15: 50% femtocell DL throughput in a single microcell environment as a function of the number of femtocells. FBS transmit power is 0 dBm.
Chapter 5

CONCLUSIONS AND FUTURE WORK

In this thesis, we consider interference mitigation in MIMO-based cellular systems. First, we developed a scheduling algorithm for an uncertain interference environment in single-tier cellular systems. Studies in [18] grouped the interfering MIMO modes into two categories. The first includes STBC, OLSM and CLSM; and the second one includes MIMO BF and MRT. The distributions of the SIR for these two categories of interferers were derived in [18]. Using these, we developed a simple and conservative scheduling approach without knowledge of interference. Since the information about the interference is not available, a conservative “margin” is applied to estimate the interference, where the “margin” represents a backoff from the achievable rate in the previous packet transmission. However, because this “margin” is so conservative, the performance is not good enough, especially in low-correlated channels. Therefore, it is difficult to achieve good performance when there is no knowledge of the interference.

Besides the intra-tier interference in single-tier cellular systems, the inter-tier interference in multi-tier cellular systems is also a challenge. For inter-tier interference in femtocellular systems, we evaluated the efficacy of BF with nulling for interference mitigation in a femtocellular system. Different transmission modes at the femtocellular BSs are compared with BF with nulling. Simulation results show that BF with nulling outperforms other techniques in maintaining the macrocellular DL performance. Both macrocellular and microcellular environments were considered. A microcell has relatively smaller radius than a macrocell, and the path-loss models
for the two environments are different because of the different antenna heights. In a macrocellular environment, the interference at the macrocellular UEs is mainly from interfering MBSs, and higher transmit power for the FBSs is permissible. In a microcellular environment without interference mitigation measures, because of the lower BS transmit power and antenna height, the interference from femtocells has more effect on the microcellular performance, and, therefore, only low transmit power at the FBSs should be used. We show that applying BF with nulling at the FBSs can effectively maintain the microcellular performance even with high FBS transmit power, which allows for significantly better femtocellular throughput compared to the case where microcellular interference is controlled by lowering femto power.

To summarize, we considered scheduling and transmission algorithms to combat interference in single-tier and two-tier cellular systems. A scheduling algorithm was developed to reduce the impact of interference with no knowledge of the interference for single-tier cellular systems. Since the interference is unknown, the performance of the algorithm is not satisfying enough. Thus, one interesting problem is to devise scheduling algorithms with partial knowledge of the interference to obtain better performance, and to investigate the tradeoff between the performance and how much information is available about the interference. For two-tier femtocellular systems, here we applied BF with nulling at the FBSs to mitigate the interference from the FBSs to the MUE. This technique requires perfect channel knowledge for both the desired and interfering links at the FBSs. Therefore, another interesting problem is how to mitigate the inter-tier interference with limited CSI. Also, a combination of scheduling and transmission modes at the FBSs and MBSs might be a solution to mitigate the intra- and inter-tier interference at the same time, and achieve better performance for both macrocells and femtocells.
BIBLIOGRAPHY


