CHAPTER 5

PERFORMANCE OF MC-CDMA SYSTEM

5.1 INTRODUCTION

In this chapter the system model of MC-CDMA is presented first. Estimation of SINR is one of the major issues in analyzing the performance of MC-CDMA systems. A multi-cell environment could be generalization of two cell model to analyze SINR pattern in MC-CDMA systems. A two cell model is derived and discussed while keeping in mind the generic architecture of cellular system. In TDD mode cross slot allocation sometimes could generate heavy interference and it needs special attention in the development of MAC protocol. An adaptive resource allocation based on M-QAM method is developed and the main system parameters like capacity, BER, delay etc. are analyzed to cover the feasibility study of MC-CDMA as a possible candidate for the air interface technique in the next generation mobile networks.

5.2 MC-CDMA SYSTEM

In MC-CDMA transmission, the input bit stream is converted into $N$-parallel stream, and then each bit is spread by a CDMA code. The inverse fast Fourier transform (IFFT) modulates these bit streams to maintain orthogonality among each stream in frequency domain as shown in Figure 5.1. The output of IFFT represents $N$ low data rate parallel sub-channels. The parallel data is converted into serial and a cyclic prefix is appended before passing it to the radio frequency (RF) module.
The MC-CDMA receiver configuration for the $j^{th}$ user is shown in Figure 5.2. After removing the cyclic prefix, the remaining samples are serial-to-parallel converted to be demodulated by FFT. The $N$-serial data are de-spread by the CDMA code and then converted back to serial to represent the user data.

**Figure 5.1 MC-CDMA transmitter**

**Figure 5.2 MC-CDMA receiver**
The signal of an \( i^{th} \) subcarrier can be denoted as

\[
S_k^i(t) = \sum_{n=0}^{N-1} b_k^i \ c_k^i \ e^{j2\pi(f_0+nf_d)t}
\]  

(5.1)

here \( N \) is the number of subcarrier, \( b_k^i \) is the \( i^{th} \) input symbol for a \( k^{th} \) user, \( f_0 \) is the base carrier frequency, and \( f_d \) is the subcarrier separation.

The received signal for the \( k^{th} \) user can be given by

\[
r_{k,i} = \xi_k^i H_k^i S_k^i + N_k^i
\]

(5.2)

where \( \xi_k^i \) is channel gain, \( H_k^i \) is channel function, \( S_k^i \) is signal strength, and \( N_k^i \) is noise variance for \( i^{th} \) sub-carrier.

### 5.2.1 SINR Estimation

In MC-CDMA with TDD, each slot will carry many user data on different channel separated and identified by Walsh-Hadamard code. Considering intra-cell and inter-cell interference separately in a multi-cell environment, the signal to noise ratio for each user’s \( i^{th} \) subcarrier can be modeled as

\[
SINR_i = \frac{P_r \cdot SF}{I_{int} + I_{ext} + N_o W}
\]

(5.3)

where \( P_r \) is the received power, \( SF \) is the spreading factor, \( I_{int} \) is the internal noise within the cell, \( I_{ext} \) is external noise coming from other cells, \( N_o \) is the noise power spectral density, and \( W \) is the total transmission bandwidth.

To approximate link gain, the received power \( P_r \) at base station (BS), can be related to the transmit power \( P_t \) of the mobile station (MS) as (Lee 2008)
\[ P_r = \lambda d^{-v}P_t \]  \hspace{1cm} (5.4)

where \( d \) is the distance between BS and MS and \( \lambda \) is a constant. In mobile communication, the loss of power in propagation is inversely proportional to the 4th power (i.e., \( v = 4 \)) of the distance between transmitter and receiver.

In MC-CDMA a channel is represented by number of subcarrier, and the number of subcarrier needed to support an application is dictated mainly by the bandwidth requirement. Further, the subcarrier selection is based on their current SINR and the estimated BER.

### 5.2.2 Two Cell Model

A system model for MC-CDMA in multi-cell environment can be built by generalizing the two cell model. While considering two cell approach, a total of four cases arise: (i) cell1 uplink cell2 uplink, (ii) Cell1 downlink cell2 uplink, (iii) Cell1 downlink cell2 downlink, and (iv) Cell1 uplink cell2 downlink. Here cell1 represents a home cell for tagged mobile, and cell2 a cell in the first tier of interfering cells.

#### 5.2.2.1 Cell 1 Uplink Cell 2 Uplink

Suppose \( m_k \) be the number of MS served by a channel, where \( k = 1,2,3,\ldots, K \). Let \( P^i_k \) denote the transmit power of \( i^{th} \) subcarrier, and \( H^i_k \) the channel gain between \( k^{th} \) MS and its BS. The internal interference \( I_{int} \) in uplink for \( i^{th} \) subcarrier carrying part of \( k^{th} \) MS data may be given by

\[
I_{int}^i = \sum_{k=1}^{m_k} \sum_{i=1}^{l_k} H^i_k P^i_k \]  \hspace{1cm} (5.5)

To compute external interference \( I_{ext} \), it is assumed that the same sub-carriers are used in neighboring cells. Let \( m_j \) be the number of MS served
in a $j^{th}$ cell, where $j = 1,2,...,J$ represents $J$ neighbor cells. Now $I_{ext}$ on $i^{th}$ subcarrier may be expressed as

$$I_{ext}^i = \sum_{j=1}^{J} \sum_{k=1}^{m_j} \sum_{i}^{l_k} H_{j,k}^i P_{j,k}^i$$  \hspace{1cm} (5.6)$$

where $H_{j,k}$ the link gain between $k^{th}$ MS in the neighboring cell and the tagged BS, and $P_{j,k}^i$ the transmit power of $k^{th}$ MS on $i^{th}$ subcarrier to support its QoS requirement in its cell.

### 5.2.2.2 Cell 1 Downlink Cell 2 Uplink

Most commonly, data in downlink channels (for example in W-CDMA) are transmitted with orthogonal codes. Assuming perfect time synchronization between MS and BS, and the channel is of the flat fading type, orthogonality is preserved during downlink slot, and hence the internal noise $I_{int}$ is absent. But multipath propagation damages the orthogonality. An orthogonality factor ($\eta$), which is the percentage of downlink orthogonality remaining at the mobile receiver, is introduced to compute $I_{int}$. It is 1 for a signal without multipath, and near zero in Rayleigh fading environment.

The internal interference $I_{int}$ on $i^{th}$ subcarrier arising due to non-orthogonality of the received signals is given by

$$I_{int}^i = \sum_{i=1}^{l} \eta_i H_i P_i$$  \hspace{1cm} (5.7)$$

where $P_i$ is the transmitter power of the BS, $H_i$ the channel gain, and $\eta_i$ the corresponding orthogonality factor for the $i^{th}$ subcarrier.
The external interference $I_{\text{ext}}$ is computed similar to eqn. (5.6), but the channel gain is different here. The $I_{\text{ext}}$ may be expressed as

$$I_{\text{ext}}^i = \sum_{j=1}^{J} \sum_{k=1}^{m_j} \sum_{l_j}^{l_k} H_{j,k}^{\text{ms},i} P_{j,k}^{i}$$  \hspace{1cm} (5.8)$$

where $H_{j,k}^{\text{ms},i}$ is the link gain between $k^{th}$ MS in neighbor cell and the tagged MS, and $P_{j,k}^{i}$ the transmit power of $k^{th}$ MS for its $i^{th}$ subcarrier.

5.2.2.3 Cell 1 downlink Cell 2 downlink

The internal interference $I_{\text{int}}$ arising due to non-orthogonality of the received signals is given by eqn. (5.7).

The BS present in interfering cell $j$ will cause interference to the downlink signal of tagged mobile. Now the $I_{\text{ext}}$ can be represented as

$$I_{\text{ext}}^i = \sum_{j=1}^{J} \sum_{l_j}^{l_k} H_{j,k}^{\text{ms},i} P_{j,k}^{bs,i}$$  \hspace{1cm} (5.9)$$

where $H_{j,k}^{\text{ms},i}$ is the link gain between the interfering BS and the MS, and $P_{j,k}^{bs,i}$ is the transmit power of the BS.

5.2.2.4 Cell 1 uplink Cell 2 downlink

The internal interference $I_{\text{int}}$ is computed as in eqn. (5.5). The external interference $I_{\text{ext}}$ is computed similar to eqn. (5.8).

$$I_{\text{ext}} = \sum_{j=1}^{J} \sum_{k=1}^{m_j} \sum_{l_k}^{l_k} H_{j,k}^{\text{bs},i} P_{j,k}^{bs,i}$$  \hspace{1cm} (5.10)$$

where $H_{j,k}^{\text{bs},i}$ the link gain between a tagged BS and BS of interfering cell $j$, and $P_{j,k}^{bs,i}$ the transmit power of $j^{th}$ BS for the $i^{th}$ subcarrier.
5.3 CROSS SLOT ALLOCATION ANALYSIS

In MC-CDMA due to traffic asymmetry and the consequent difference in slot allocation from cell to cell, the system suffers from both intra-cell and inter-cell interference as shown in Figure 5.3. For example, mobiles in a cell may use uplink slots and, at the same time, the base station of an adjacent cell may use downlink slot to transmit signals. In this situation, the uplink (downlink) channel in a cell can have interference from the downlink (uplink) of the adjacent cell and, in turn, this results in capacity degradation.

![Figure 5.3 Interference in uplink and downlink because of cross-slot](image)

Although a different slot allocation within a cell is also possible, but it is not implemented in practice as it will cause heavy interference in both uplink and downlink. Here, we assume that slot allocation within a cell is same and perfectly synchronized between BS and MS. The cross slot allocation between two cells is the case for traffic asymmetry as shown in Figure 5.4. The number of cross slot allocations can be governed by the base station controller (BSC) in a location area consisting of multiple cells. Since cross slot allocation normally causes increased interference, it will be a major factor in supporting quality of service and also capacity of the system.
5.3.1 SINR Computation in Cross Slot Allocation

In this section, a deterministic simplified approach is presented to analyze cross slot allocation. Let $N_c$ be the number of cross slots in each TDD frame. Assuming that channels are evenly distributed over the same type slots in every cell, let $n_1$ and $n_2$ be the number of channels assigned to cross slots in cell1 and cell2 respectively. To support multimedia application, let the required data rate be $R_u$ in the uplink and $R_d$ in the downlink.

5.3.1.1 Cell1 Uplink Cell2 Downlink

Let us assume that, at a particular time, a slot in Cell1 is for uplink and in cell2 it is for downlink. In the SINR computation, the source of noise is due to presence of other users, while assuming that all MS are perfectly synchronized with uplink and downlink slots in a TDD frame. Further it is assumed that a perfect power control mechanism is implemented, so that BS receives equal power from all MS in its cell. The background thermal noise $N_0$, can be ignored as it is very small compare to the $I_{int}$ and $I_{ext}$.

Let the equal power received by BS from every MS in cell1 is $P_{rms1}$. The internal noise, $I_{int}$ can be related to the number of channels in cell1 and the number of cross slot as
\[ I_{\text{int}} = \left( \frac{n_1}{N_c} - 1 \right) P_{\text{rms}1} \] (5.11)

The external noise \( I_{\text{ext}} \) in cell1 is the downlink signal originating from BS in cell2, and can be given by

\[ I_{\text{ext}} = \frac{\lambda (2D)^{-4} n_1 P_{\text{bs}2}}{N_c} \] (5.12)

where \( 2D \) is the distance (i.e., cell radius of \( D \)) between two BS, \( P_{\text{bs}2} \) is the transmit power at BS2.

If \( W \) is the total spreading bandwidth, the spreading factor, (also called processing gain) for uplink, \( SF_u \) is given by

\[ SF_u = \frac{W}{R_u} \] (5.13)

Now the SINR for the uplink slot in cell1 can be given by

\[ \text{SINR} = \frac{r^{-4} P_{\text{ms}1} SF_u}{\left( \frac{n_1}{N_c} - 1 \right) P_{\text{rms}1} + (2D)^{-4} P_{\text{bs}2} n_2/N_c} \] (5.14)

where \( r \) is the distance between the tagged MS and the BS in cell1.

The received power \( P_{\text{rms}1} \) can be related to \( P_{\text{ms}1} \) by

\[ P_{\text{rms}1} = \lambda r^{-4} P_{\text{ms}1} \] (5.15)

Defining \( P_{\text{bs}2}/P_{\text{rms}1} = \rho \), and \( r/D = \gamma \), eqn. (5.14) can be rewritten as

\[ \text{SINR}_{UL} = \frac{SF_u, N_c}{(n_1 - N_c) + (\gamma/2)^4 \rho} \] (5.16)
5.3.1.2 SINR computation for Cell 1 DL Cell 2 UL

Consider MSs in cell2 are uniformly distributed, and \( R_0 \) denotes the mean distance between interfering MSs in cell2 and the tagged MS in cell1. Defining \( \rho_m = \frac{P_{rms2}}{P_{tbs1}} \) and \( \gamma_m = \frac{R_0}{r} \), and taking advantages of eqn. (5.14) it can be easily shown that SINR during downlink slot in cell1 is given by

\[
SINR_{DL} = \frac{SF_d \cdot N_c}{(m_2 - N_c) + \eta (\gamma_m/2)^4 \rho_m} \tag{5.17}
\]

where \( \eta \) is the orthogonality factor for downlink channel, and

\[
SF_d = \frac{w}{R_d} \tag{5.18}
\]

5.4 SUBCARRIER AND SLOT ALLOCATION ALGORITHM

The M-QAM technique is incorporated in MC-CDMA to make the system more adaptive and efficient. The Subcarrier and Slot Allocation (SSA) algorithm adaptively manages the system resources to meet the quality of the service requirements of an application. The selection of subcarriers is carried out based on its current SINR to support a minimum BER.

The BER for the \( i^{th} \) subcarrier corresponding to M-QAM is given by (Goldsmith et al 1997)

\[
BER_i = \frac{1}{5} \exp \left[ \frac{(-1.5 \cdot SINR_i)}{M - 1} \right] \tag{5.19}
\]

where \( SINR_i \) is the signal to noise ratio for the \( i^{th} \) subcarrier, and \( M \) is the constellation points in M-QAM.

The SSA algorithm as shown in Figure 5.5 decides whether an outgoing slot is to be declared as uplink/downlink based on the existing capacity of the present slot.
First, the SINR is calculated using the formulae shown in section 5, that falls under any one of the four cases considered there. Since the CDMA based systems are inherently interference limited, the SINR is recomputed
every time based on the new call arrival rate and hence, the addition of a new subcarrier in a slot. The new call considered here includes handoff user too. The BER is estimated using eqn. (5.19) based on the SINR and a high modulation order \( M=8 \). If \( BER > 10^{-3} \), then the order of modulation \( M \) is reduced and BER is computed again, and this process is repeated till BER falls below \( 10^{-3} \) and the corresponding \( M \) value is retained to be used for order of modulation in M-QAM. If BER does not falls below \( 10^{-3} \) and \( M = 2 \), then the next slot is declared as of the same status (e.g. uplink if the current slot is uplink) and new calls are accommodated in new slots. Based on the existing SINR and bandwidth requirement of the application, the number of subcarriers is allocated to these new calls. If the accumulated bandwidth \( BW_c \) i.e., number of subcarriers is just enough to meet the requirement \( BW_r \), the resource allocation is complete for a user and the algorithm takes next call to be processed.

5.5 RESULTS AND DISCUSSION

Simulations were carried out for the four cases of uplink and downlink scenario of MC-CDMA system. First, the BER performance of the proposed algorithm is simulated in the presence of a Rayleigh channel. Different Walsh codes were used for spreading user data on each subcarrier. A total of four cases were considered to evaluate BER performance in the presence of Rayleigh channel and additive white Gaussian noise. The major simulation parameters are listed in Table 5.1.

5.5.1 BER Performance for Different Cases

First, to study the behavior of Rayleigh channel for 8-QAM, a BER plot as shown in Figure 5.6 under three circumstances is simulated. As per the analytical formula, a theoretical BER plot is generated. Next, by semi analytical and also by Monte Carlo technique with a limit of 10 errors and \( 10^8 \)
bits, two more simulations results are generated. Here, the aim of this experiment is to understand the independent behavior of M-QAM Rayleigh Channel. Clearly BER comes down faster for higher values of SINR in Monte Carlo based simulation.

The four cases considered here represent different scenarios as listed in Table 5.2. Each case represents a traffic direction, and the interference pattern changes accordingly. The BER in Case1 as shown in Figure 5.7 follows a higher path than Case2 as in uplink base station suffers from both intra cell and inter cell interference from a large number of users.

**Table 5.1 Simulation Parameters**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>10 MHz</td>
</tr>
<tr>
<td>Spreading Factor</td>
<td>128</td>
</tr>
<tr>
<td>Length of Walsh Code</td>
<td>8</td>
</tr>
<tr>
<td>FFT Length</td>
<td>1024</td>
</tr>
<tr>
<td>Modulation (M-QAM)</td>
<td>2 - 8</td>
</tr>
<tr>
<td>Rayleigh Channel</td>
<td></td>
</tr>
<tr>
<td>(Sample Period T_s , Doppler Shift Δf)</td>
<td>Ts=0.01s, Δf=10 Hz</td>
</tr>
<tr>
<td>Number of users</td>
<td>15-30</td>
</tr>
<tr>
<td>Noise Power Spectral Density</td>
<td>1.1565*10^{-8}</td>
</tr>
<tr>
<td>Cell Radius, R</td>
<td>500m</td>
</tr>
<tr>
<td>Interfering Distance: d_{min} , d_{max}</td>
<td>d_{min} = 100m, d_{max} = 2*R</td>
</tr>
</tbody>
</table>


Figure 5.6 Simulation of M-QAM Rayleigh channel

Table 5.2 Simulation Scenario

<table>
<thead>
<tr>
<th>Case</th>
<th>Cell1</th>
<th>Cell2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case1</td>
<td>Uplink (UL)</td>
<td>Uplink (UL)</td>
</tr>
<tr>
<td>Case2</td>
<td>Uplink (UL)</td>
<td>Downlink (DL)</td>
</tr>
<tr>
<td>Case3</td>
<td>Downlink (DL)</td>
<td>Downlink (DL)</td>
</tr>
<tr>
<td>Case4</td>
<td>Downlink (DL)</td>
<td>Uplink (UL)</td>
</tr>
</tbody>
</table>
5.5.2 SINR Estimation

The distance ratio considered in Figure 5.8 represents the ratio of distance between the tagged mobile and the base station to the mean distance of interfering mobile in the same cell. As indicated in eqn. (5.4), the received power inversely varies with the fourth power of distance in wireless communication, a small change in distance causes large variations in interference pattern and hence the SINR.

The distance ratio considered in Figure 5.9 is applicable to all four cases as it is used in computation of external interferences. Interestingly Case 4 performs better as the distance defined here is the ratio of mean distance from interfering MS to the tagged MS to the distance between tagged MS and its BS.
Figure 5.8 SINR vs. distance ratio in internal interference

Figure 5.9 SINR with respect to distance ratio for external interference
5.5.3 The Effect of Orthogonality Factor

As discussed earlier, the intra cell interference in downlink is caused by orthogonality factor. Figure 5.10 shows the BER performance with respect to variation in the orthogonality factor. In case of cross slot, i.e., Case 4, there could be heavy interference as the interfering user in a neighboring cell may be near to the tagged mobile. Case 3 shows a slightly better performance, as the interference is caused by a base station only, as the neighboring cell is in downlink. A curve fitting function is used to plot BER here.

![Figure 5.10 BER with respect to orthogonality factor in internal interference](image-url)
5.5.4 Capacity Estimation

The capacity (bit/sec/Hz) of each subcarrier in a given slot is computed during simulation of the proposed algorithm and is plotted in Table 5.3. In the given scenario, since the maximum order of modulation employed is only eight, at most the achievable capacity will be 3 bit/sec/Hz, as predicted by the Shannon’s capacity formula. Clearly, the bit loaded for all slots is not linear here, as it represents the random traffic present in a particular instant. The capacity or loading pattern could be linear by considering more number of users and variety of multimedia services.

Table 5.3 Slot-wise Traffic and Subcarrier Loading

<table>
<thead>
<tr>
<th>Traffic \ Slot No</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic Distribution (Number of subcarriers)</td>
<td>46</td>
<td>45</td>
<td>38</td>
<td>45</td>
<td>47</td>
<td>33</td>
<td>43</td>
<td>15</td>
</tr>
<tr>
<td>Subcarrier Loading (bit/sec/Hz)</td>
<td>2.1</td>
<td>1.8</td>
<td>1.6</td>
<td>1.8</td>
<td>1.6</td>
<td>2.0</td>
<td>2.0</td>
<td>2.1</td>
</tr>
</tbody>
</table>

5.5.5 Delay Estimation

Figure 5.11 shows the processing delay of the SSA algorithm with respect to number of users. This delay is incurred in processing new calls. The new calls may be originating from a new user or due to a hand off call. This delay must be upper bounded to serve the real time multimedia traffic. The delay observed here corresponds to the Pentium(R)-4 CPU 3.4 GHz processor with a 0.99 GB of RAM employing Microsoft Window XP operating system.
5.6 SUMMARY

An MC-CDMA system in the TDD mode is modeled and analyzed to support an adaptive resource allocation algorithm. The multi-cell environment was modeled and simulated by generalizing a two-cell model. The interference analysis has two major components: the intra cell and inter cell. Based on the traffic direction, four cases were modeled and analyzed.

The proposed SSA algorithm judiciously allocates the subcarrier and slot. The distance ratio greatly affects the SINR performance of MC-CDMA systems. It was observed separately for inter cell and intra cell scenario. A change of 0.2 in distance ratio in the computation of internal interference, causes a corresponding change of around 0.5 dB in SINR. A similar pattern is observed in computation of external interference. The BER performance for different cases provides an overview of the system analysis in the presence of
AWGN noise and Rayleigh channel. Two cases, Case2 and Case3 for BER are not simulated and presented here, as after analyzing Case1 and Case2 it becomes quite predictable. The capacity (carrier loading) observed here is less than 3bit/sec/Hz mainly due to use of a lower order of modulation ($M=8$).