CHAPTER 6

PERFORMANCE OF OFDMA IN TDD MODE

6.1 INTRODUCTION

In this chapter first a system model of OFDMA is presented. The interference analysis in a typical cellular environment supporting OFDMA technique in TDD mode is presented to estimate the system parameters: SINR and BER. To study the feasibility of the system to support multimedia, an adaptive resource allocation protocol is proposed and investigated. The result presented here includes SINR, BER, and processing delay of the system. A comparison of OFDMA and MC-CDMA under given conditions is offered to have a deterministic view of resource allocation problem in multicarrier systems.

6.2 SYSTEM MODEL

In OFDMA, each user equipment sends data to the base station on a set of assigned subcarriers on which the transmitter modulates data symbols. The transceiver system splits an input data stream into \( N \) parallel data streams, each representing a low data rate channel. The basic technique is sometimes referred to as the discrete multi-tone modulation, because, instead of using a single carrier, a large number of evenly spaced subcarriers are modulated using \( M \)-ary of QAM. Each QAM symbol stream is then mapped to a tone at a unique frequency and transformed together using the IFFT to yield the time-domain waveform as shown in Figure 6.1. Thus, each uplink/downlink OFDMA symbol contains data for several user equipments on disjoint sets of
subcarriers. The IFFT ensures that the subcarriers are orthogonal to each other and allow a high spectral efficiency with a total symbol rate close to the Nyquist rate. The spectrum utilization increases further by operating the OFDMA system in TDD, as in this mode the same carrier frequency is used alternately for transmission and reception. Also, the channel state information can be easily made available to the base station by employing TDD technique. Due to channel reciprocity, we may transmit pilot sequences in the uplink direction before the data transmission in the downlink.

![OFDMA transmitter diagram](image)

**Figure 6.1 OFDMA transmitter**

The received signal is fed into the N-FFT for multicarrier demodulation, and then the desired subcarriers are selected for each user’s M-QAM decoding as shown in Figure 6.2. The FFT function converts the time signal back into the frequency domain, which reconstructs the frequency/amplitude map created at the transmitter. The subcarrier, order of modulation $M$, and the slot information to decode the signal is conveyed to each receiver by base station periodically.

Let $x^i_k$ be the input data sequence for the $k^{th}$ user, and, if there are $N$ sub carriers, then complex base band signal resulting from $N$-point IFFT and a cyclic pre/postfix of length $m_1$ and $m_2$ can be given by (Ahmad R S Bhai et al 2004)
where $-m_1 < t < \frac{N + m_2}{f_s}$, and $f_s$ is the rate at which this cyclic pre/postfix appended data is passed to analog module that contains digital to analog converter and RF modulator.

![Figure 6.2 OFDMA receiver](image)

A generalized representation of OFDMA signal for a $k^{th}$ user that includes a window function is given by (Ahmad R S Bhai et al 2004)

$$s_k(t) = \sum_{i=0}^{N-1} x_k^i e^{j2\pi N f_s t}$$  \hspace{1cm} (6.1)$$

where $x_{i,p}$ is the input data during $p^{th}$ OFDMA block, and $w(t)$ is the window function also called pulse shaping function. The OFDM block duration $T$ can be expressed as

$$T = \frac{N + m_1 + m_2}{f_s}$$  \hspace{1cm} (6.3)$$
The transmitted signal $s_k(t)$ passes through a time varying channel and the received signal for $k^{th}$ user can be represented by

$$r_k(t) = \int_0^\infty x_k(t - \tau) h_k(t, \tau) d\tau + n(t)$$

(6.4)

where $x(t)$ is the input signal, $h(t)$ the channel impulse response, and $n(t)$ represents the Additive White Gaussian Noise (AWGN).

The received signal is sampled at $m/f_s$ for $-m_1 < m < (N + m_2)$. Assuming that there is no inter block interference and window function satisfies the condition $w(i - 1) = \delta_{i,p}$, the output after FFT transformation can be given by (Ahmad R S Bhai et al 2004)

$$\bar{S}_k(t) = \frac{1}{N} \sum_{m=0}^{N-1} \left[ \sum_{i=0}^{N-1} H^i x^i e^{j2\pi m_i/N} + n(m) \right] e^{-j2\pi k m^m/N}$$

(6.5)

where $H^i, x^i$ and $n(m)$ are the channel frequency response, input data, and AWGN noise respectively for the $k^{th}$ user on $i^{th}$ subcarrier.

### 6.3 ANALYSIS OF INTERFERENCE PATTERN

In OFDMA systems the same subcarriers can be used in the alternate tiers of cell, but not in the same cell, thus avoiding the possibility of intra cell interference. So, the SINR in OFDMA mainly depends on inter cell interference. For example, MS in a cell may use uplink slots and at the same time an MS in the second tier cell may use a downlink slot to receive signals. This creates different interference pattern based on the direction of traffic in home cell and interfering cell.
The slot allocation within a cell cannot be non-uniform, as it will cause heavy interference, and also TDD requires perfect synchronization between BS and MS. Cross slot allocation is with respect to two different cells as shown in Figure 6.3. The interference due to cross slot allocation will be predominant when the distance between tagged mobile and interfering mobile is small, thereby deciding the link quality and hence the data rate.

In particular, the cross slot allocation when tagged MS uses downlink and interfering MS using same subcarriers uses uplink can cause heavy interference to the tagged mobile. It could be the worst case scenario for system design and hence resource allocation algorithm has to treat it as a special case for subcarrier and power allocation. The analysis carried out here assumes uniform power allocation to all subcarriers thereby it does not include any water filling mechanism.

![Figure 6.3 Different slot allocations in a TDD frame](image)

### 6.3.1 SINR in Multi-cell TDD Environment

In OFDMA with TDD, each slot will carry many user data on different channels. Considering the interference in a multi-cell environment, the signal to noise ratio for each user’s $i^{th}$ subcarrier can be modeled as
\[ \text{SINR}_i = \frac{P_r}{I + \frac{(BN_0)}{N}} \] 

(6.6)

where \( P_r \) is the received power, \( I \) is the interference power coming from other cells, \( N_0 \) is the noise power spectral density, \( B \) is the total transmission bandwidth, and \( N \) is the total number of sub carriers. The second term in denominator of eqn. (6.6) rather represents Additive White Gaussian Noise.

Since the each orthogonal subcarrier carries a M-QAM modulated user data, the BER formula (as mentioned in Section 5.4) for the \( i^{th} \) subcarrier,

\[ \text{BER}_i = \frac{1}{5} \exp \left( \frac{(-1.5 \cdot \text{SINR}_i)}{M-1} \right) \]

is directly applicable here.

As discussed earlier in Chapter 5, the link gain estimation is based on the assumption that the loss of power in propagation is inversely proportional to the 4\(^{th} \) power of the distance between transmitter and receiver. In OFDMA, a channel is represented by the number of subcarriers, and hence an incremental approach can be followed to meet the total data rate requirements of an MS. The number of subcarriers needed to support an application is dictated mainly by the channel condition i.e., the current SINR of a subcarrier and the bandwidth requirement.

Considering a two cell approach, four cases arise: (i) cell1 uplink cell2 uplink, (ii) Cell1 uplink cell2 downlink, (iii) Cell1 downlink cell2 uplink, and (iv) Cell1 downlink cell2 downlink. Here cell1 represents a home cell for tagged mobile, and cell2 a cell in second tier of interfering cells.

(i) **Cell1 Uplink Cell2 Downlink:** Suppose \( M \) be the number of MS served by a channel, Let \( P_{ti} \) denote the transmit power of \( i^{th} \) subcarrier, and \( d \) the distance between \( i^{th} \) MS and its BS.
The interference $I$ caused by BS in cell2 can be represented as

$$I = \sum_{i=1}^{N_m} P_{tt} \cdot d^{-4}$$  \hspace{1cm} (6.7)

where $N_m$ is the number of subcarriers used by BS in cell2.

(ii) **Cell1 Downlink Cell2 Uplink**: Assuming same $N_m$ subcarriers are utilized by $M$ users in cell2. The interference $I$ can be modeled as

$$I = \sum_{i=1}^{M} \sum_{k=1}^{N_m} P_{tt} \cdot d^{-4}$$  \hspace{1cm} (6.8)

(iii) **Cell1 Uplink Cell2 uplink**: In this case the computation of the interference $I$ is similar to eqn. (6.7) but it is experienced by BS because of employing same subcarriers by a MS in other cells.

(iv) **Cell1 Downlink Cell2 Downlink**: The BS in cell2 causes interference to the MS in cell1 and can be represented by an equation similar to eqn. (6.8).

### 6.4 SUB CARRIER ALLOCATION ALGORITHM

The Sub Carrier Allocation (SCA) algorithm as shown in Figure 6.4 manages the subcarrier in a slot to meet the link quality requirement of an application. The selection of subcarriers is carried out based on its current SINR to support a minimum BER. The slot management to decide whether an outgoing slot is to be declared as uplink/downlink is totally based on the existing traffic requirement in a cell. For example, when more MS wants download application, the number of downlink slots in a frame will be more than the uplink slot, but even in the worst case when all MS wants to
download data, at least one slot will be for uplink as the channel state information is periodically needed by the BS.

![Flowchart](image)

**Figure 6.4 The SCA algorithm**

First, the SINR is calculated using the formulae shown in Section 6.3.1, that falls under any one of the four cases considered. The BER
is computed 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 corresponding sub carrier is rejected. Based on the existing SINR and bandwidth requirement of an application, the number of subcarriers is allocated to these new calls.

If the accumulated bandwidth ($BW_c$) i.e., the number of subcarrier is just enough to meet the requirement ($BW_r$), the resource allocation completes for a user and the algorithm takes next call to be processed.

6.5 RESULTS AND DISCUSSION

Simulations were carried out for the four cases of uplink and downlink scenario of OFDMA system. First, the BER performance of SCA algorithm in presence of AWGN and Rayleigh channel is presented. The major simulation parameters are listed in Table 6.1. A test bench was created based on the mathematical model presented in Section 6.2 and 6.3.

<table>
<thead>
<tr>
<th>Table 6.1 Main Simulation Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Parameters</strong></td>
</tr>
<tr>
<td>Bandwidth</td>
</tr>
<tr>
<td>FFT Length</td>
</tr>
<tr>
<td>Modulation (M-QAM)</td>
</tr>
<tr>
<td>Rayleigh Channel:</td>
</tr>
<tr>
<td>Sampling Interval ($T_s$)</td>
</tr>
<tr>
<td>Max. Doppler Shift ($\Delta f$)</td>
</tr>
<tr>
<td>Number of users</td>
</tr>
</tbody>
</table>
6.5.1 SINR and BER Analysis

The four cases considered here represent the different scenario as listed in Table 6.2. Each case represents a traffic direction, and defines the interference pattern accordingly. Figure 6.5 – 6.8 shows the BER corresponding to different SINR pattern representing four cases. The lower range of SINR (3dB-5.5dB) in Case4 is due to its interference pattern which could be higher than the other three cases as the mobile stations in uplink in interfering cell may be at the near side of the tagged mobile. The interference is less in the rest of the cases, causing higher the range of SINR and hence lower BER. All four plots (Figure 6.5 - 6.8) can not be combined into a single one as the estimated value of the SINR doesn’t fall in common ranges. Since the test bench created here represents the OFDMA system, many additional parameters need to be considered. Table III shows the other simulation parameters used here. The typical power considered here is low as the user employs many subcarriers and total power is sum of power in each subcarrier. Further in order to represent the pico cell environment, the cell size or in the other words, distance between tagged mobile and interfering mobile from neighboring cell is considered small (550 – 700 m).

<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>
Table 6.3 Other Simulation Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of sub carriers, N</td>
<td>128</td>
</tr>
<tr>
<td>Total number of Pilots, N_p</td>
<td>128/8 = 16</td>
</tr>
<tr>
<td>Total number of data sub carriers, S</td>
<td>N - N_p</td>
</tr>
<tr>
<td>Guard interval length, G_i = N/4</td>
<td>128/4 = 32</td>
</tr>
<tr>
<td>Pilot position interval, T_p</td>
<td>8</td>
</tr>
<tr>
<td>Channel length, L</td>
<td>16</td>
</tr>
<tr>
<td>Number of iteration in each evaluation</td>
<td>5000</td>
</tr>
<tr>
<td>Power ranges per subcarrier</td>
<td>1.2mW - 2mW</td>
</tr>
<tr>
<td>Distance range for interfering mobile</td>
<td>550m – 700m</td>
</tr>
</tbody>
</table>

Figure 6.5 BER performance in Case1
Figure 6.6 BER performance in Case2

Figure 6.7 BER performance in Case3
Figure 6.8 BER performance in Case 4

Figure 6.9 shows the SINR of the system with respect to number of users, assuming constant distance from interfering MS/BS. Case 4 (DL, UL) represents a scenario where SINR follows a lower path than the other cases considered here. Case 2 (UL, DL) also follows a similar path like Case 4, but for increasing the number of users, the difference between Case 2 and Case 4 exceeds 1.5 dB. Case 3 (DL, DL) shows a higher SINR curve, but as the number of users increases, SINR comes down even lower than Case 2.
Case2 and Case4 represent a cross slot allocation, and need to be discussed separately. For example, in Case4, there could be heavy interference at tagged MS as interfering users in neighboring cell may be at the shortest distance to the tagged mobile. In Case2 the interference received at BS for the tagged mobile signal is caused by the surrounding BS and will be constant after system deployment.

The distance ratio considered in Figure 6.10 and Figure 6.11 is defined as the ratio of distance between tagged MS and its BS to the distance between tagged MS and the interfering MS/BS. As can be seen in Figure 6.10, the difference in SINR in Case1 and Case2 is more than 1dB. In Case3 and Case4, the gap in SINR increases with the distance ratio, and exceeds 1.5dB when the distance ratio approaches unity.

As in the mobile environment the received power varies inversely with $4^{th}$ power of the distance, a small change in distance ratio can cause large variation in SINR. The maximum distance ratio considered in Case3 and
Case4 as shown in Figure 6.11 is 1, assuming that the MS in first tier interfering neighboring cell, even at the shortest distance could not be less than distance the MS and its BS.

![Figure 6.10 SINR vs. distance ratio in Case1 and Case2](image1)

![Figure 6.11 SINR vs. distance ratio Case3 and Case4](image2)
6.5.2 Processing Delay Analysis

The delay is one of the main QoS parameters to serve real time multimedia services in any network. The SCA algorithm assumes that the number of uplink and downlink slot is decided by the BS dynamically based on the prevailing traffic load in a particular cell. In other words, the ratio of uplink to downlink slot varies from time to time in every cell. The delay encountered by the data packet very much depends on the number of uplink/downlink slot, and hence a study of processing delay with respect to the uplink to downlink ratio is immensely desirable here. Although this delay is not noticeable for a smaller number of users (up to 10) under different slot ratio as shown in Figure 6.12, but for larger number of users it becomes prohibiting factor for the protocol design.

![Figure 6.12 Delay with different ratio of uplink to downlink](image)

6.5.3 OFDMA vs. MC-CDMA in TDD Mode

The proposed SCA algorithm for OFDMA works on the same principles of adaptiveness as SSA in MC-CDMA, but the slot management is
directly not incorporated in the SCA. The number of uplink/downlink slots in the frame of OFDMA system is dynamically decided based on the present traffic requirements, and not on the problem of capacity optimization. Further, in the estimation of the SINR in OFDMA system it is assumed that the intra-cell interference is absent, which is quite justifiable in the system design. The MC-CDMA offer benefits like additional channel gain, but lags behind OFDMA when it comes to basic performance parameters like BER and SINR. The BER in particular for Case2 in OFDMA is below $7 \times 10^{-3}$ for an SINR of 5dB, but in MC-CDMA it is above $10^{-2}$ for the same SINR. In all the four cases considered here, OFDMA outperforms MC-CDMA with respect to SINR and BER. The delay pattern for both of these system are acceptable for a multimedia traffic but, for larger number of users, it rises exponentially for the MC-CDMA systems.

6.6 SUMMARY

A system model and analysis of OFDMA in TDD mode was presented to facilitate the feasibility study of the adaptive resource allocation. The analysis of interference pattern is simpler than MC-CDMA as in OFDMA the intra cell interference is inherently absent. In cross slot allocation, the estimated SINR are low; specifically, in Case4 (Refer Figure 6.8) it lies between 3dB to 5.5dB. The distance ratio greatly affects the SINR computation. A change of 0.05 in distance ratio causes a variation of more than 0.5 dB in SINR when MS operates in downlink.

The delay analysis was presented as the proposed resource allocation algorithm is intended for multimedia application. The ratio of uplink to downlink dictates the packet delay for larger number of users. The OFDMA outperforms the MC-CDMA but to have channel gain additional coding mechanism will be needed.