CHAPTER 6

RESULTS AND DISCUSSION
6.1 MODULATION SCHEMES

Digital data is transferred in an OFDM link by using a modulation scheme on each subcarrier. A modulation scheme is a mapping of data words to a real (In phase) and imaginary (Quadrature) constellation (IQ constellation). For example 256-QAM (Quadrature Amplitude Modulation) has 256 IQ points in the constellation, constructed in a square with 16 evenly spaced columns in the real axis and 16 rows in the imaginary axis. The number of bits that can be transferred using a single symbol corresponds to \( \log_2(M) \), where \( M \) is the number of points in the constellation, thus 256-QAM transfers 8 bits per symbol. Each data word is mapped to one unique IQ location in the constellation [74].

6.1.1 EFFECTS OF CONSTELLATION POINTS

Increasing the number of points in the constellation does not change the bandwidth of the transmission, thus using a modulation scheme with a large number of constellation points, allows for improved spectral efficiency [75]. For example 256-QAM has a spectral efficiency of 8 b/s/Hz, compared with only 1 b/s/Hz for BPSK. However, the greater the number of points in the modulation constellation, the harder they are to resolve at the receiver. As the IQ locations become spaced closer together, it only requires a small amount of noise to cause errors in the transmission. This results in a direct trade off between noise tolerance and the spectral efficiency of the modulation scheme.
The BER of an OFDM system is dependent on several factors, such as the modulation scheme used, the amount of multipath, and the level of noise in the signal. However, the performance of OFDM with just AWGN is exactly the same as that of a single carrier coherent transmission using the same modulation scheme. Similarly, a single OFDM subcarrier (since the subcarriers are orthogonal to each other, this does not effect the performance in any way) is exactly the same as a single carrier transmission that is quadrature modulated with no band pass filtering. The transmitted amplitude and phase is held constant over the period of the symbol and is set based on the modulation scheme and the transmitted data. This transmitted vector is then updated at the start of each symbol. This results in a $sinc$ frequency response, which is the required response for OFDM.

The optimal receiver for such a single carrier transmission uses a coherent matched receiver, which can be implemented by mixing the signal to DC using an IQ mixer. This results in an IQ output that describes the amplitude and phase of the received modulated carrier. The amplitude and phase of the transmitted signal is constant over the symbol period, and so the optimal method of removing the most noise from the signal is to use an integrate-and-dump filter. This filter averages the received IQ vector over the entire symbol, then performs IQ demodulation on the average. The demodulation of an OFDM signal is performed in exactly the same
manner. In the receiver a FFT is used to estimate the amplitude and phase of each subcarrier. The FFT operation is exactly equivalent to IQ mixing each of the subcarriers to DC then applying an integrate-and-dump over the number of samples in the FFT [76].

Thus, the FFT performs the same operation as the matched receiver for the single carrier transmission, except for a bank of subcarriers. Thus, OFDM will have the same performance as a single carrier transmission with no band limiting.

6.2.1 MERITS OF OFDM SYSTEM

Most propagation environments suffer from the effects of multipath propagation. For a given fixed transmission bandwidth, the symbol rate for a single carrier transmission is very high, where as for an OFDM signal it is N times lower, where N is the number of subcarriers used. This lower symbol rate results in a lowering of the ISI. In addition to lowering of the symbol rate, OFDM systems can also use a guard period at the start of each symbol. This guard period removes any ISI shorter than its length. If the guard period is sufficiently long, then all the ISI can be removed.

Multipath propagation results in frequency selective fading that leads to fading of individual subcarriers. Most OFDM systems use Forward Error Correction (FEC) to compensate for the subcarriers that suffer from severe fading. The adaptive modulation scheme proposed in this research matches the modulation scheme of each subcarrier to its SNR. The additional spectral efficiency of those subcarriers that have a
SNR greater than the average (due to constructive interference) tends to compensate for subcarriers that are subjected to fading (destructive interference). As a result of this, the performance of such an OFDM system in a multipath environment is similar to its performance in an AWGN channel [77]. The performance of the OFDM system will be primarily determined by the noise seen at the receiver. However, the performance of a single carrier transmission will degrade rapidly in the presence of multipath.

63 SIMULATION SET UP

The effect of AWGN on OFDM was simulated for a wide range of subcarrier modulation schemes. The lower density modulation schemes show the data mapping used. The results presented show the BER performance as a function of the channel SNR. Other simulations in this thesis, present the performance of OFDM under a range of detrimental effects. These simulations measure the performance by finding the effective SNR of the channel instead of the BER [78, 79]. These simulations show the communication performance that corresponds to an equivalent AWGN SNR. The results presented in this section can then be used to predict the BER for the particular modulation scheme used. The symbol error rate of most common modulation schemes has been derived in algebraic form. However, the derivation of the BER is difficult due to possibility of multiple bit errors per symbol. Additionally the BER for only square QAM modulation schemes, such as 16-QAM, 64-QAM, 256-QAM, etc, can be calculated directly. To overcome this problem the BER performance of OFDM was
obtained by using simulation. There are four main categories of modulation presented, which are, coherent QAM, coherent PSK, differential QAM, and differential PSK [80].

The following performance measures are determined in the present research work and comparative study is done. The metrics obtained includes (but not limited to)

(i) Total system data rate
(ii) Mean SNR variation for individual user
(iii) User Bandwidth allocations
(iv) User data rate variations

The results obtained are presented here partially for total system data rate and user bandwidth allocations alone (for brevity), and a detailed discussion on the other performance measures is presented in the thesis.

6.3.1 TOTAL SYSTEM DATA RATE

The total system data rate for the proposed adaptive MIMO-OFDM with two-dimensional CSI estimator is shown in figure 6.1
Figure 6.1: Average system throughputs for Adaptive user bandwidth allocation MIMO-OFDM Scheme

For comparison study, the same measure is obtained for three existing schemes namely FDMA allocation, TDMA allocation and Random user bandwidth allocation schemes and the plots are shown in figure 6.2, figure 6.3 and figure 6.4 respectively.
Figure 6.2: Average system throughputs for FDMA user bandwidth allocation scheme

Average System Throughput: 196.8 Mbps

Figure 6.3: Average system throughputs for TDMA user bandwidth allocation scheme

Average System Throughput: 245.4 Mbps
6.3.2 MEAN SNR VARIATION FOR INDIVIDUAL USER

The mean SNR variation for individual users for the four different schemes is presented in figure 6.5 and figure 6.6 to figure 6.8 respectively.

Figure 6.5 Mean SNR for individual user for Adaptive user bandwidth allocation MIMO-OFDM scheme
Figure 6.6 Mean SNR for individual user for FDMA user bandwidth allocation scheme

Figure 6.7 Mean SNR for individual user for TDMA user bandwidth allocation scheme
6.3.3 USER BANDWIDTH ALLOCATIONS

The user bandwidth allotted dynamically for the proposed scheme is shown in figure 6.9.

Figure 6.8 Mean SNR for individual user for random user bandwidth allocation scheme

Figure 6.9: Adaptive User Bandwidth allocations
Similarly, the same measure for the three other comparison schemes is shown in figure 6.10 to figure 6.12.

Figure 6.10: User Bandwidth allocations for FDMA scheme

Figure 6.11: User Bandwidth allocations for TDMA scheme
6.3.4 USER DATA RATE VARIATION

The user data rate variation for the four different schemes is shown in figure 6.13 and figure 6.14 to figure 6.16.

Figure 6.13 User data rate Variation for Adaptive MIMO-OFDM Scheme
Figure 6.14 User data rate Variation for FDMA scheme

Figure 6.15 User data rate Variation for TDMA scheme
6.4 CONTINUATION OF RESULTS

<table>
<thead>
<tr>
<th></th>
<th>Average system Throughput (Mbps)</th>
<th>Mean SNR for each user (dB)</th>
<th>User BandWidth allocation</th>
<th>% Time user data rate variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adaptive MIMO-OFDM (Proposed)</td>
<td>288</td>
<td>22.5</td>
<td>50% of the time &lt; 7 dB</td>
<td>100 %</td>
</tr>
<tr>
<td>FDMA</td>
<td>198.8</td>
<td>25</td>
<td>7 dB uniform</td>
<td>98.48%</td>
</tr>
<tr>
<td>TDMA</td>
<td>245.4</td>
<td>Random but &gt; 25</td>
<td>Very high</td>
<td>88.41%</td>
</tr>
<tr>
<td>RANDOM</td>
<td>249.3</td>
<td>25</td>
<td>7 dB uniform</td>
<td>85.55%</td>
</tr>
</tbody>
</table>

Table 6.1 Summary of system performance when using different user allocation schemes
6.4.1 INFERENCE

The Average system throughput value is best in the proposed Adaptive MIMO-OFDM scheme (288 Mbps). The Mean SNR required for individual user to achieve a desired throughput is optimal in Adaptive MIMO-OFDM scheme i.e. 22.5 dB only. Thus, in the proposed Adaptive MIMO-OFDM scheme it is possible to achieve best results at lower Mean SNR value itself. The User Bandwidth to be allocated is minimum in Adaptive MIMO-OFDM scheme compared to other schemes. The TDMA scheme is least preferred and requires large bandwidth to be allocated for individual users. Similarly, the % time User data rate variation is effective in the proposed MIMO-OFDM scheme and all the time % time user data exceeds zero Mbps. For e.g. in the random modulation scheme for 14.45% of the time the user data rate is zero Mbps which indicates poor utilization.