Abstract

The combination of Massive MIMO and OFDM technologies gives great advantages to the wireless communication system as Massive MIMO has high diversity gain to improve the BER performance and OFDM technology has the ability to convert frequency selective fading to a set of independent flat fading channels to suppress the inter-symbol Interference(ISI).In addition, the Massive MIMO technology has the ability to eliminate the noise with giving higher reliability to OFDM system due to diversity gain and with higher speed due to spatial multiplexing. In this thesis, Massive MIMO-OFDM system BER (Bit Error Rate) performance is simulated when different detector types are used in the system for different modulation schemes and compared with linear detectors as well while the channel is frequency selective. Furthermore, by comparison the system performance is shown when the different modulation schemes are used and the performance of non-ordering detectors are simulated to detect the significance of ordering detection on the performance.

.

.

Chapter One

1.1 Introduction

MIMO (Multiple Input and Multiple Output) technology has become existent recently as it has higher data rate for fixed bandwidth and the capacity of the communication channel increases without adding more bandwidth to the communication system. In addition, when the number of the receiver antennas grows very largely then the level of interference and fading effects decrease much. Furthermore, by using different type of detectors the performance of the system can be compared with different scenarios and this all leads to increasing the reliability of the system compared to SISO (single input and single output) systems [1], [2].

MIMO gets advantages of both MISO and SIMO features as it combines both techniques and multiple antennas are used in both transmitter and receiver sides. However, in order to improve capacity and get better space diversity in MIMO technology, it is a great challenge to increase the number of antennas in transmitter and receiver sides such as increasing transmit antennas to 8 and receiver antennas to 200 which raise the possibility of getting advantages from multiple versions of the same signal that comes from multiple paths to the receiver to predict the transmitted stream [1], [3]. When the number of antennas increases unlimitedly, the effect of noise and intra-cell interference will be vanished and the Massive MIMO technique can give large capacity to fulfil the Shannon capacity requirement and the performance of the system improves enormously. However, the complexity of the system increases especially from the receiver side [3].

Massive MIMO is used to improve the data rate but it cannot solve the frequency selective channel problem alone and so to overcome this problem, MIMO system is combined with OFDM technology to convert frequency selective channel to a set of parallel flat fading independent channels. This is the best way to use both advantages in wireless communication system, as OFDM (Orthogonal Frequency Division Multiple Access) which uses high number of parallel narrow-band subcarriers to convey information between transmitter and the receiver of the wireless communication system. OFDM technology is efficient against multipath channel, and cyclic prefix (CP) is added to remove inter-symbol interference which is due to multipath effects. In order to recover the original information stream which goes through MIMO Channel, detectors are used such as zero-forcing, MMSE (Minimum Mean Square) and V Blast to improve BER versus SNR. If the response of the channel known such as frequency selective then it is easier for the receiver side with equalizers to remove the effects of the channel [4].

In this dissertation, Massive MIMO-OFDM with frequency selective channel is simulated with using four types of detectors (Zero-forcing detector, MMSE and ZF-SIC and MMSE-SIC) for modulation schemes of 16QAM, 32QAM and 64QAM with making comparison between their simulation results.

1.4 Literature Review on MIMO system

1.4.1 MIMO versus point to point wireless communication Systems

Point to point wireless communication was invented, the first time, successfully by Marconi around 1897 when he invented wireless telegraphy. Later, this idea flourished to more advanced point to point systems such as microwave circuits and GSM mobile cellular system(second generation) in the early of the 1980th after AMPS (Advanced Mobile Phone Service) when there was air interface between the base stations and mobile users. The design of wireless systems traditionally were focused on increasing reliability of the air communication channel to improve diversity and averaging interference such as using frequency hopping technique in the base stations of the mobile cellular system[5]. However, lately, concentration on the progression of Spectral efficiency has been exploited and for this reason, the communication theory shifted towards the MIMO communication system. In conventional point to point wireless communication system, fading channels and specifically multipath channels had a great role in losing original information that reached the receiver and normally when there was destructive fading, so some techniques such as good cell planning was used to decrease this effect but this had not solve this problem in some scenarios. Thus, the MIMO communication system was invented more widely to get more advantage of multipath fading by sending the same information stream through multiple transmitting antennas to the receiver and in the receiver side more than one receiver antenna was used to receive the signals coming from all the transmitting antennas to make the probability of successful transmission higher and by this the diversity gain was increased [6].

However, the MIMO system has been used to increase the data rate by grouping more than one information stream from each transmitting antennas in one timeslot then sending them with the same bandwidth or by other meaning, multiple independent information streams are transmitted by the multiple transmit antennas in the same time to improve data rate transmission, and this is named by spatial multiplexing [7], [8]. So the capacity has increased in this way which is not possible in the conventional point to point wireless systems without expanding bandwidth or adding more capacity resources **.**Other advantages of MIMO system is array gain which is the coherent combination of the wireless signal in the receiver to improve performance. However, if the number of antennas becomes very large then the capacity of the system becomes very close to the Shannon capacity limitation and the noise and intra-cell interference effects removed from the system and the performance of the system improves hugely. Using MIMO system with OFDM technology has big challenges on mitigating the inter-symbol interference and converting frequency selective fading to flat fading for better analysis and improving BER enhancement[3],[9].

1.4.2 MIMO Performance Analysis for ZF and MMSE Detectors

As it's been stated above, without demand of more bandwidth for higher data rate, MIMO system has higher data rate than traditional point to point wireless communication system as it is very expensive to increase the bandwidth and sometimes it is impractical solution, and also through MIMO usage, the link has higher reliability due to the space diversity .It provides more capacity as in the different timeslot each transmit antenna transmits an independent information symbol ,so the increasing data rate depends on N_t factor [4]. The detection methods has great influence on the MIMO receiver performance, for instance, zero-forcing as linear equalizer which inverts the channel frequency response and it is perfect to suppress Inter-symbol interference(ISI) when there is noiseless channel; however, when the channel noise increases then it amplifies the noise, so it is good for noiseless channels mostly. Figure 1.1 shows one of the equalizer models:

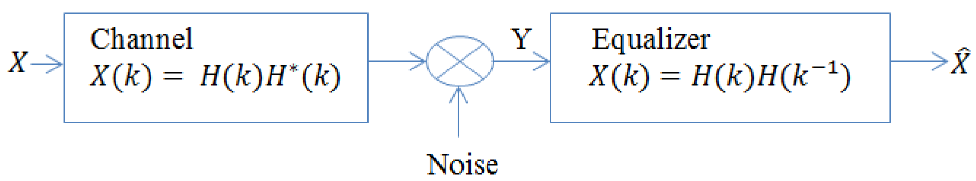

Figure 1.1 Zero-forcing Equalizer Model [10]

The zero-forcing equalizer can be written as:

$$Zf\_Equalizer = \frac{1}{H(k)H(k^*)^{-1}} \tag{1.1}$$

The aim of ZF is to find the filter coefficients of W_{zf}

$$X_k = \sum_{n=-k}^{N} W_k H_{k-n} \tag{1.2}$$

Where $W_{zf} = (H^H H)^{-1} H^H$ (1.3)

However, in MMSE, for each time sample to minimize the error between the desired signal and the equalized signal, a set of coefficients can be found.

The transfer function of the filter coefficients of MMSE is

$$\text{MMSE (z)} = \frac{1}{F(Z)F^*(Z^{-1})+N_0} \tag{1.4}$$

To find the filter coefficients, the minimum mean square error method is used to minimize this criterion:

$$\text{MMSE} = E\{[W_{mmse}y - x][W_{mmse}y - x]^H\} \tag{1.5}$$

$$W_{mmse} = [H^H H + N_0 I]^{-1} H^H \tag{1.6}$$

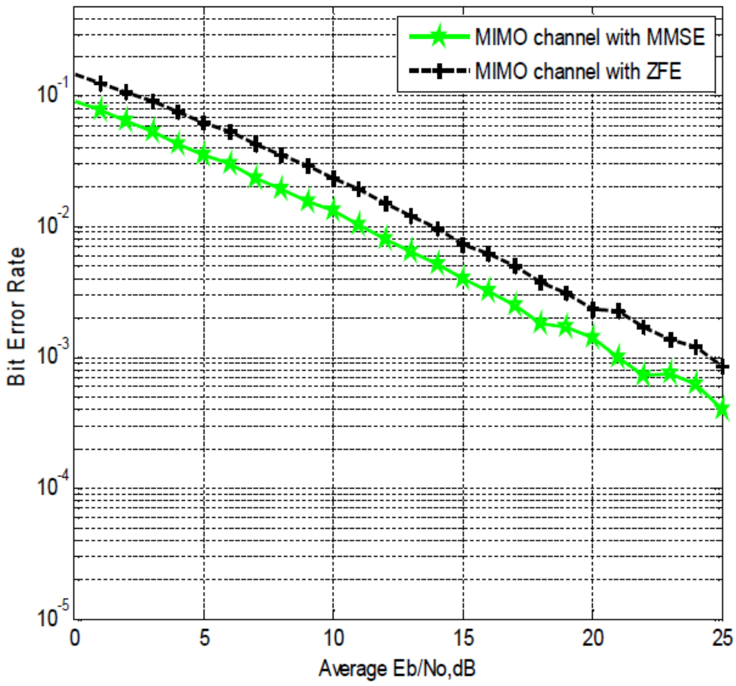

Figure 1.2 BER for BPSK with 2*2MIMO systems with ZFE and MMSE [10]

It is shown that in Figure 1.2 by increasing the SNR, the BER enhancement for both equalizers are improving but the decrement of BER in ZF Equalizer is less than the BER decrement of MMSE Equalizer for the same SNR. In BER of 10^{-2} MMSE has higher SNR by 2dB and this is proof of that using equalizers improves the BER performance versus SNR but the MMSE equalizer improves the performance better than the ZF equalizer when there is same multipath channel condition [10].

Another significant point that in high spectral efficiency modulation schemes such as 64QAM, the BER performance is less than the lower modulation schemes such as 4QAM due to Shannon Capacity theorem, there is a trade of between spectral efficiency and BER performance [11].As shown in Figure 1.3, zero-forcing equalizer is used to cancel the effect of 9 taps multipath channel [12].

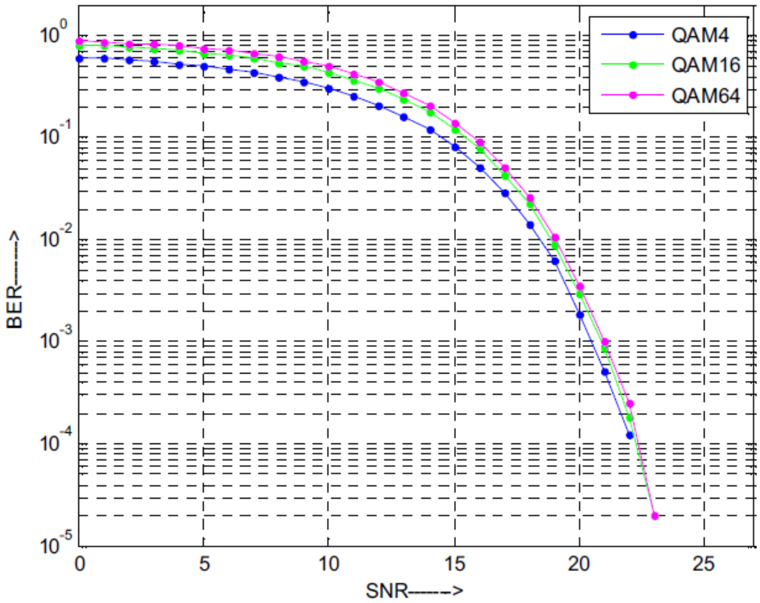

Figure 1.3 BER versus SNR for 4QAM, 16QAM and 64QAM Modulation Schemes with ZF Equalizer [12]

1.4.3 MIMO Performance Analysis for V-Blast Detectors

V Blast divides the information stream into some sub-streams and in the same time and frequency, it transmits them through multiple antennas, which has multiple transmit and receive antennas, and also V-Blast is a single user scheme. It has two main advantages, improving diversity gain and improving BER performance of the MIMO system. It integrates linear and nonlinear detection process by operating the interference nulling, interference cancellation and optimal ordering to improve performance. The performance of the MIMO system after V-Blast detection, is also different according to the modulation schemes in the same way as it is in linear detectors as shown in figure 1.4 [13].

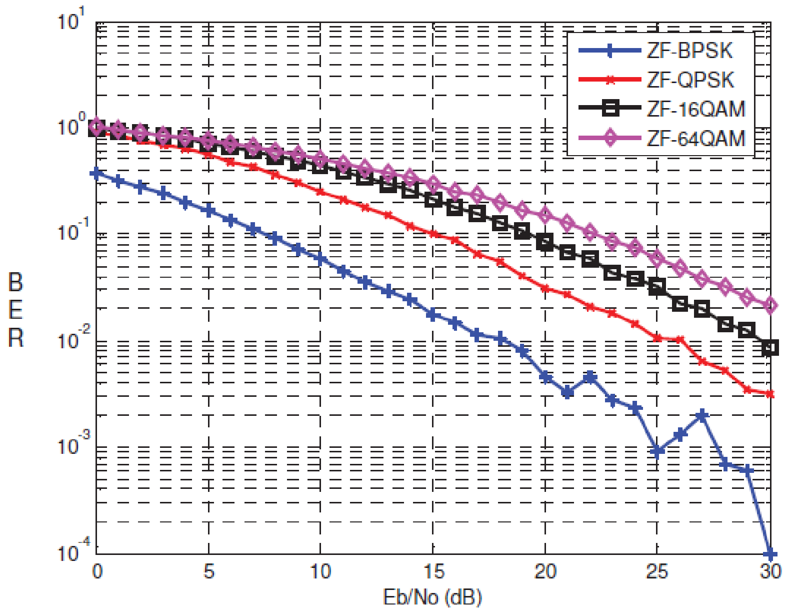

Figure 1.4 V-Blast ZF Receiver performance for different modulation schemes with Flat fading [13].

Zero-forcing-SIC is used and shown in the Figure 1.4 above, the BPSK has the best BER performance compared to the other high spectral efficiency modulation schemes for the same SNR.

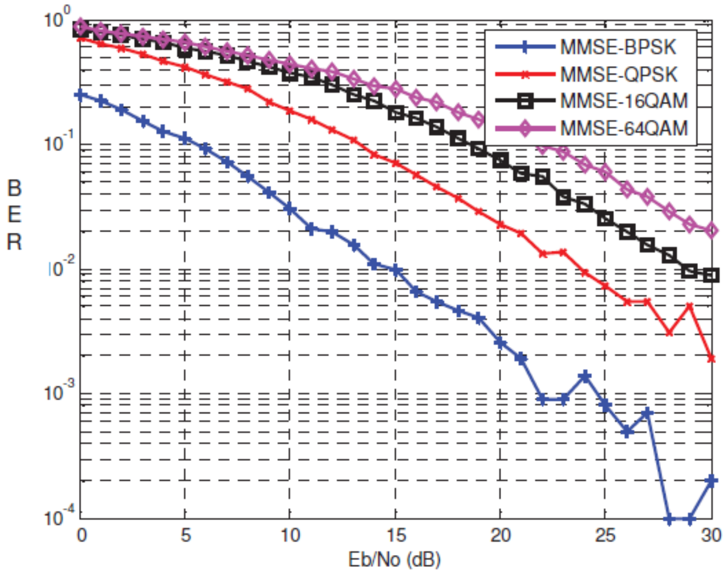

Figure 1.5 V-Blast MMSE Receiver performance for different modulation schemes [13]

Compared to ZF SIC, V-Blast MMSE has better BER performance for the same SNR as MMSE receiver minimizes errors caused by noise and mutual interference among the co-channel signals but with lower level of quality [13].

Chapter Two

2. Background Theory

2.1 OFDM Technology

Due to the demand of high speed date rate and fast wireless technology and the usage of multicarrier modulation which can decrease the effects of multipath fading problem without lowering the data rate, Orthogonal Frequency Division Multiplexing (OFDM) has been established. In addition, OFDM as multi-carrier system challenges single-carrier transmission as single carrier system is not very efficient for high data rates as wide bandwidth is required for higher data rates which leads to increase the signal bandwidth compared to coherence bandwidth then inter-symbol interference will occur during transmission. Thus, So OFDM multi-carrier transmission can decrease the effects of this problem more effectively. The whole bandwidth of OFDM are divided into narrowband subcarriers that are orthogonal to each other and each sub-carrier uses modulation schemes at a low symbol rate and for bandwidth efficiency the spectra of subcarriers are overlapping and the guard bands are not necessary due to orthogonality property which increases the spectral efficiency of the OFDM system[14],[15].

For the implementation of orthogonal signals, Inverse Fourier Transform (IFFT) and Fast Fourier Transform (FFT) are used in the transmitter and receiver side respectively. In the transmitter of OFDM, each subcarrier is dedicated to transmit some data streams after modulation process such as 16QAM Modulator, so before transmission, high speed serial data streams is converted into low speed parallel data streams through serial to parallel convertor then converted to time domain by IFFT then back to serial data stream to be ready for transmission after cyclic prefix insertion. However, in the receiver side, this process is controversy; the received signal is converted to frequency domain before demodulation process and finally the signal converted back to serial data stream. Moreover, the most significant step in the OFDM technology is adding cyclic prefix (CP) which is a copy of the last part of the OFDM symbol which should be longer than the length of the path of the transmitted signal normally to remove the effect of multipath which causes inter-symbol interference (ISI) when the transmitted signal experience different paths with time delays before reaching the receiver. In the receiver side, this cyclic prefix (CP) is discarded from the symbol again before demodulation [16], [15].

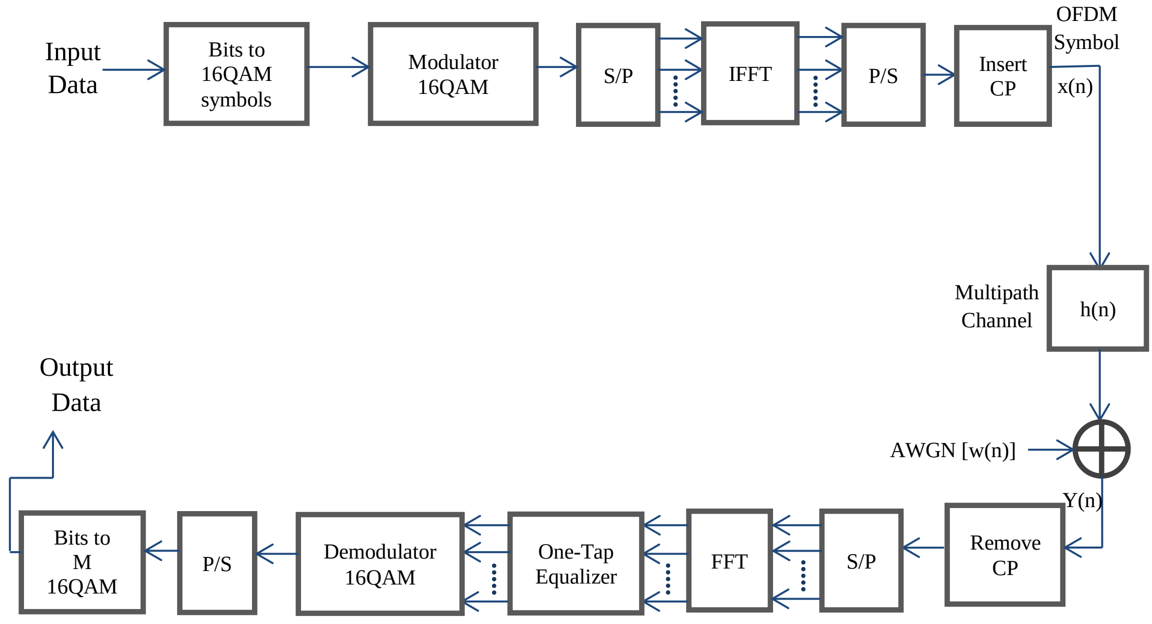

Figure 2.1 OFDM System Structure [15]

2.2 Massive MIMO-OFDM Technology

The data rate of wireless communication system can be increased by using OFDM technology but high capacity cannot be achieved without increasing channel resources because it requires very high spectrum efficiency despite the capacity requirement of overcoming the channel fading in the multipath channel environment. In addition, spatial diversity gained by spatially separated antennas in a multipath environment can be used as a strong advantage by MIMO technology to obtain spatial diversity property and combat signal fading as well besides of MIMO capacity gain. When the number of antennas increased to a large number to construct a Massive MIMO system, the link reliability increases due to diversity gain of MIMO system which means intending to receive the same information bearing signals in the multiple antennas or to transmit them from multiple antennas and a higher transmission speed is achieved due to spatial multiplexing which means transmitting multiple independent data streams simultaneously by multiple transmit antennas and also the capacity of the system increases as well, So by using both technologies together in a wireless communication system Quality of service (QoS) and transmission rate are improved [4],[17]. In terms of detectors, V-Blast

Detectors can be used with MIMO system to improver BER performance and this gives more advantage to OFDM system when it is combined with MIMO technology .As shown in Figure 2.2, each MIMO transmit and receive antenna has its own modulator and demodulator respectively and this means each MIMO antenna enjoys the full advantage of OFDM technology besides of MIMO advantages it has [18].

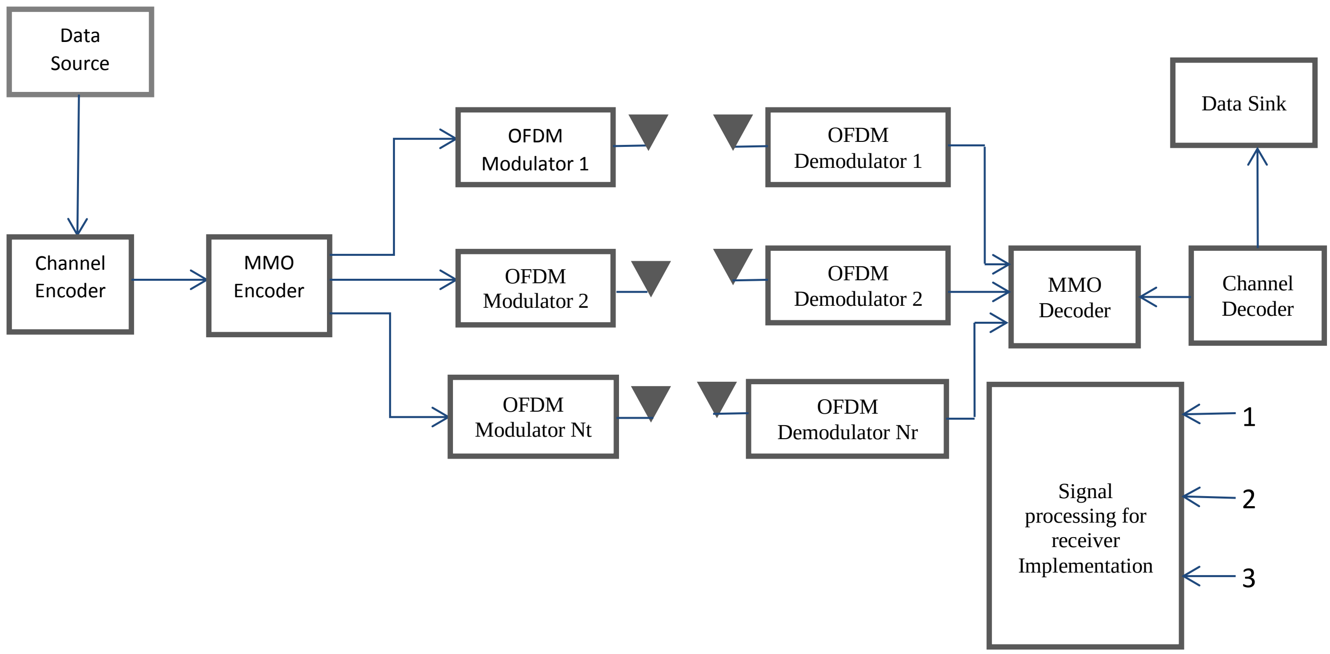

Figure 2.2 Massive MIMO-OFDM Sample System [18]

2.3 MIMO Channel Model

The impulse response in time domain for a MIMO system can be expressed as $h_{ij}(\tau;t)$ where τ is the time delay variable and t is the time variable and the MIMO system has N_t transmit antennas and N_r receive antennas. Thus, the channel is defined as N_t*N_r for $\mathrm{H}(\tau;t)$ as shown below in (2.1):

$$H(\tau;t) = \begin{pmatrix} h_{11}(\tau;t) & \cdots & h_{1N_t}(\tau;t) \\ \vdots & \ddots & \vdots \\ h_{N_r1}(\tau;t) & \cdots & h_{N_rN_t}(\tau;t) \end{pmatrix} \quad (2.1)$$

Where $s_j(t)$ is the transmitted signal from j transmit antennas as j=1,2,3,4,…..,N_t and so

So the received signal y(t) can be is characterized as:

$$y(t) = \sum_{j=1}^{N_t} h_{ij}(\tau;t) \otimes S_j(\tau) + n(t) \quad (2.2)$$

Where n(t) is white additive noise [19].

2.4 Multipath Fading

When the transmitted signal received by the receiver from different paths then multipath phenomena occurs, in this case the fading is small scale fading as its signal power varies sharply and it has two types which are Flat fading and frequency selective fading [15].

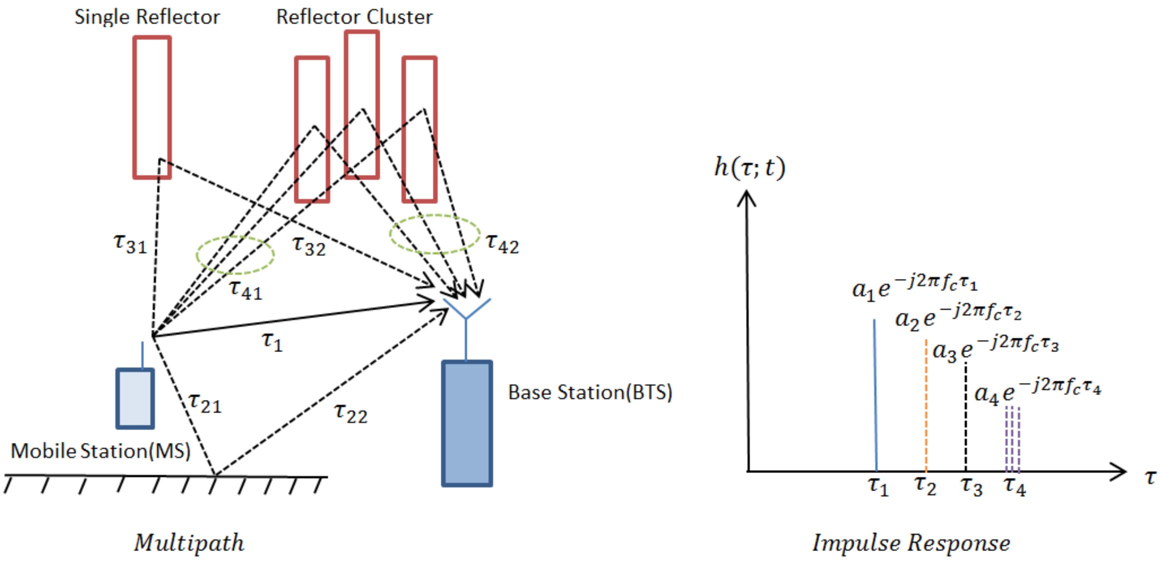

Figure 2.3 Multipath Channel Scenario [15]

2.5 Frequency Selective Channel

When the signal bandwidth is greater than coherence bandwidth of the channel, the channel is frequency selective so:

$W > \Delta C$ where W is the signal bandwidth and ΔC is the coherence bandwidth.

$\Delta C \approx \frac{1}{\tau_{rms}}$ where τ_{rms} is the delay spread of the channel.

$$\tau_{rms} = \sqrt{\left(\frac{1}{P_l}\sum_{l=1}^{L} \tau_l^2 P_l\right) - \tau_{av}^2} \tag{2.3}$$

L is the number of paths and P_t is the total power, τ_{av} is the average delay spread [20].

The receiver gets same versions of the transmitted signal from many different paths which can be represented mathematically as:

$$S(t) = \sum_{l=1}^{L} \alpha_l \, s(t - \tau_l) \tag{2.4}$$

Where τ_l is the time delay for each path and α_l is the complex gain and it is assumed constant if the transmitter and receiver are stationary, so the channel response will be:

$$h(t, \tau) = \sum_{l=1}^{L} \alpha_l \, \delta(\tau - \tau_l) \tag{2.5}$$

The channel is dependent on frequency response [21], [22].

For the MIMO system, the frequency selective channel matrix can be represented as

$$H(\tau) = \sum_{l=1}^{L} h^l \, \delta(\tau - \tau_l) \tag{2.6}$$

The channel Matrix characterized as

$$H^l = \begin{pmatrix} h^l_{11} & \cdots & h^l_{1Nt} \\ \vdots & \ddots & \vdots \\ h^l_{Nr1} & \cdots & h^l_{NrNt} \end{pmatrix} \qquad (2.7)$$

The dimensions of H^l is the matrix of $N_r * N_t$ and so $h^l_{j,i}$ has a plural propagation coefficient from transmit antennas to the receive antennas and the above matrix size is dependent on the number of transmit and receive antennas in MIMO system. For frequency selective MIMO channel, the receive signal is represented as:

$$y(t) = \sum_{l=0}^{L-1} H^l s(t) + n \qquad (2.8)$$

Where n is the white Gaussian Noise [23], [24].

2.6 Flat Fading Channel

It is small scale fading channel which is caused when the coherence bandwidth (ΔC) of the channel is greater than the signal bandwidth W, or the delay spread τ_{rms} is smaller the symbol duration T, the channel is flat fading [17]. For MIMO Model, each sub-channel of each antenna forms an equivalent Rayleigh channel and $|h_{ji(t)}|$ satisfies Rayleigh distribution, so each sub-channel characterized as [25]:

$$h_{ji}(\tau, t) = h_{ji(t)} \delta(\tau - \tau_0) \qquad (2.9)$$

Where i=1, 2,….,N_t j=1,2,…..,3, N_r

In MIMO-OFDM system, cyclic prefix converts frequency selective fading channel into a set of flat fading channels to overcome inter-symbol interference [25],[26].

2.7 Rayleigh Channel Distribution

Rayleigh fading is regarded as small scale fading channel which there is no component of line of sight for the signal. In Rayleigh fading, the amplitude of the signal is randomly changes and its envelop is the Rayleigh distribution. It occurs due to scattering environment with many obstacles that leads to multiple versions of the signal by reflection towards the receiver. Noise properties and the channel characteristics obeys the Rayleigh fading channel algorithm and there is no main signal component, the phase of the signal is uniformly distributed between 0 to 2π and the mean of the signal is zero, thus the probability density function (pdf) can be characterized as:

$$f(\gamma) = \begin{cases} \frac{\gamma}{\sigma^2} \exp\left(\frac{-\gamma}{\sigma^2}\right) & \gamma \geq 0 \\ 0 & \gamma < 0 \end{cases} \qquad (2.10)$$

Where σ^2 is defined as the Rayleigh Distribution Fading envelope [27].

2.8 Spatial Diversity of Massive MIMO System

One of the techniques to combat multipath fading is the space diversity technique and also it is designed to improve the wireless received signal quality and is also called antenna diversity. According to space diversity definition, it is the usage of multiple antennas to send or receive signals and it includes the diversity technique of transmitting diversity and receiving diversity. In reality, the diversity reception is obtained by multiple receiving antennas separated by different vertical height on the spatial area and the transmit diversity is sending the same information bearing signals from multiple antennas [28].

The distance between the antennas should be large enough to maintain the incoherence between received signals and ideally the distance between each antenna and its adjacent antenna is half of the electromagnetic wave length. Massive MIMO-OFDM system has large number of antennas to vanish the effect of noise and get full advantage of space diversity especially in the receiver side as the number of antennas becomes very large then the diversity technique becomes more beneficial to reduce the effect of channel fading and to improve transmission reliability and it needs other resource about massive MIMO diversity [4], [28].

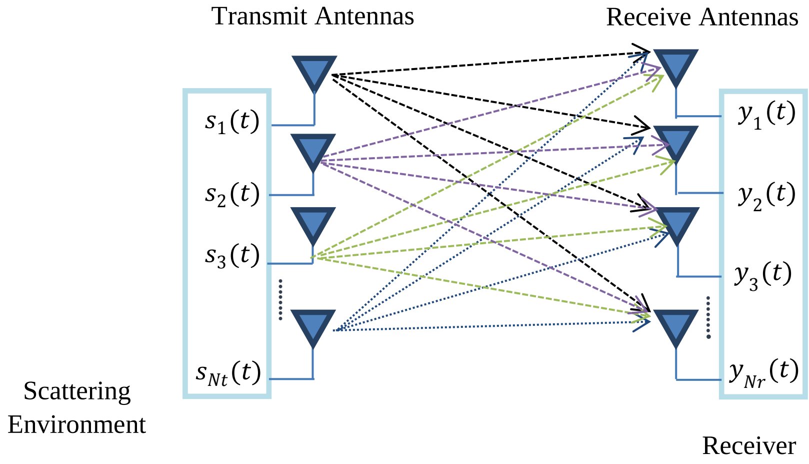

Figure (2.4) Massive MIMO Structure [29]

2.9 Spatial Multiplexing of Massive MIMO System

The capacity of massive MIMO-OFDM channel is very large due to a high number of antennas in receiver side and sometimes in the transmitter side as well; however, by using spatial diversity technique the transmission reliability of the system increases much but the transmission speed is still much lower than the capacity of the MIMO channel. Thus, spatial multiplexing is a technique used to obtain an advantage of the additional free spatial dimensions that gained from the MIMO channel and it is defined as when the multiple transmit antennas transmit independent data streams simultaneously, the maximum transmission speed achieved by the MIMO system will be the same as the MIMO channel capacity and by increasing the number of antennas especially in the receiver side, the spatial diversity increases which leads to improve the performance of the Massive MIMO-OFDM system[30],[31].

2.10 MIMO System Detectors

Detectors are used to calculate and output an estimate of the transmitted signal vector through the MIMO system channel. In this dissertation, four types of detectors are used which are zero-forcing detector(ZF), minimum mean square error(MMSE) and V Blast Detectors (ZF SIC and MMSE SIC)[32].

2.10.1 Zero-forcing Detector

Zero-forcing is a linear detector that filters the received signal by a linear filter to detect each data symbol separately in order to cancel out the interference signals and by using linear detectors the receiver complexity is reduced but with trade off with performance. Zero-forcing inverts the channel transfer matrix to cancel out the effect of the channel. The element $\hat{x}$ is estimated from the received signal y after the zero-forcing equalizer is used to remove the effect of the channel as shown in this equation [32]:

$$w_{zf} = (H^H H)^{-1} H^H \quad (2.11)$$

$$\hat{x} = \mathrm{w_{zf}} \times \mathrm{y} \quad or \ \hat{x} = (H^H H)^{-1} H^H y \quad (2.12)$$

Then each element of $\hat{x}$ is calculated with the closest transmitted symbol to demodulate the original transmitted information in the demodulator and it is concluded that the zero-forcing detector removes the co-channel interference completely but with the trade off with SNR which has effect on reducing the signal diversity of the received signal [32],[33].

2.10.2 Minimum Mean Square Error (MMSE) Detector

The MMSE is also a linear detector which is designed to minimize the mean square error of the transmitted symbol x with the estimated symbol and by using a linear filter, this detector is useful to reduce the effects of the back ground noise of the zero-forcing detector and it is shown by the equation below[32],[34]:

$$\begin{aligned} \mathrm{w_{mmse}} &= E[||\mathrm{x} - \mathrm{w^H\ y}||^2] \\ &= (\mathrm{E}\ [y\mathrm{y^H}])^{-1}\ \mathrm{E[ys^H\ ]} \\ &= H(\mathrm{H^H H} + \tfrac{\mathrm{N_0}}{\mathrm{E_s}}\mathrm{I})^{-1} \quad (2.13) \end{aligned}$$

$$\hat{x} = w_{mmse} * y$$
$$= H\,(H^H H + \frac{N_0}{E_s} I)^{-1} \times y \quad (2.14)$$

By this method, the co-channel interference is not be cancelled entirely as it does not like zero-forcing, thus it can save diversity gain, so it is less sensitive to noise and it works as a matched filter for low SNR and at high SNR it converges to zero-forcing detector[34],[35].

2.10.3 V-Blast Detectors

As shown in Figure 2.5, the linear detectors such as zero-forcing and MMSE detectors have low complexity but this cannot give good performance, so to solve this problem, the non-linear detectors with successive interference cancellation are used in MIMO systems and characterized by V-Blast Detectors [36]. There is other type of Blast detectors named by D-Blast Detector which was proposed by Foschini can give high capacity close to Shannon capacity but when the number of antennas in the transmitter and receiver increases respectively, the complexity increases and make it difficult for implementation despites the high spectral efficiency it gives, so V-Blast detectors (Vertical Bell Laboratories Layered Space Time) are more practical for the MIMO system of $N_r \geq N_t$[37].

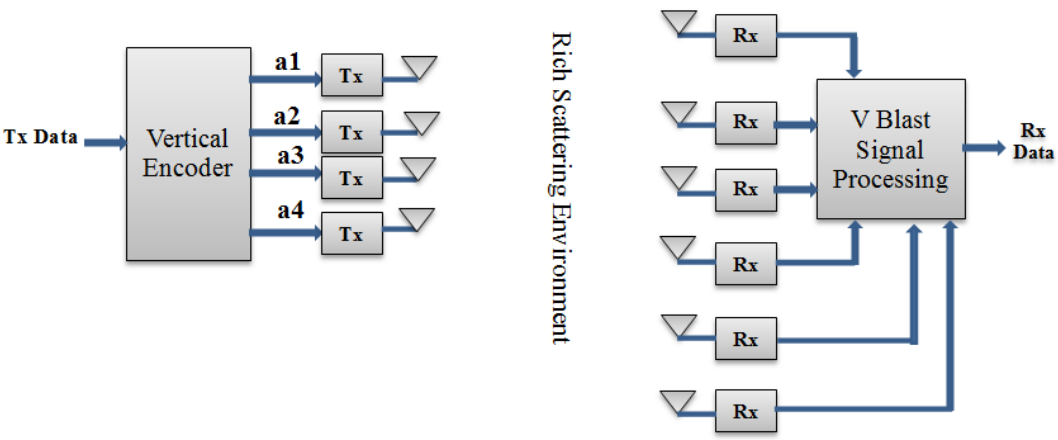

Figure 2.5 V-Blast high level system diagram [37]

As shown in Figure 2.5, when the Tx Data enter the transmitter of the MIMO system, the transmitting data(Tx) is de-multiplexed into M substreams according to the number of transmit antennas(M) then each data stream is modulated by using M modulation scheme and the power of each transmitter is proportional to (1/M)[37].After modulation, each antenna transmits the carrier signal to the environment to rich the MIMO receiver after multipath propagation, then each receiver antenna receives the signal of each transmitted antenna that was radiated through the communication channel to the MIMO receiver to be equalized by zero-forcing suppression interference cancellation (SIC) or MMSE_SIC then later to be ready for demodulation in order to get back the original information bit streams and V-Blast is regarded as single user system as divides the information of one user to a number of sub-streams and combines the traditional detection methods of zero-forcing and MMSE with more advanced detection methods of interference suppression [38].

2.10.3.1 Zero-forcing SIC Detector

It is nonlinear zero-forcing detection which performs equalization to the communication channel by cancelling the effect of each estimated symbol after detection [34]. Based on Q factorization, the interference suppression cancellation can be achieved after performing nulling process over inter-symbol interference (ISI) and by this example it can be shown:

Suppose $y = hx + n$ whether $N_r \geq N_t$ (2.15)

Where n is noise and h is the channel matrix composed of $r \times t$ and y is the received signal and x is the transmitted signal.

$$y=[\![h_1 \quad h_2 \quad \dots .h_t]\!] \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_t \end{bmatrix} + \bar{n} \qquad (2.16)$$

$$y = h_1x_1 + h_2x_2 + \cdots . \dots + h_tx_t + h_2 + \bar{n} \qquad (2.17)$$

Q factor is the pseudo inverse or left inverse of H, so $Q = H^{+}$

$$Q = \begin{bmatrix} q_1^H \\ q_2^H \\ \vdots \\ q_t^H \end{bmatrix} \quad \text{and} \quad QH = \begin{bmatrix} q_1^H \\ q_2^H \\ \vdots \\ q_t^H \end{bmatrix} [h_1 \quad h_2 \quad \ldots . h_t] = I_t \tag{2.18}$$

$$= \begin{bmatrix} q_1^H h_1 & q_1^H h_2 & \ldots \ldots . & q_1^H h_1 \\ q_2^H h_1 & q_2^H h_2 & \ldots \ldots . & q_2^H h_t \\ \vdots & \vdots & \vdots & \vdots \\ q_t^H h_1 & q_t^H h_2 & \ldots \ldots . & q_t^H . h_t \end{bmatrix} = \begin{bmatrix} 1 & 0 & \ldots \ldots . & 0 \\ 0 & 1 & \ldots \ldots . & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \ldots \ldots . & 1 \end{bmatrix} \tag{2.19}$$

$$q_1^H h_1 q_2^H h_2 = \ldots\ldots\ldots = 1 \tag{2.20}$$

$$q_1^H h_2 q_2^H h_1 = \ldots\ldots = 0 \tag{2.21}$$

So it is concluded that:

$$q_i^H h_j = \begin{cases} 1 & \text{if } i = j \\ 0 & \text{if } i \neq j \end{cases} \tag{2.22}$$

$$\hat{y}_1 = q_1^H (h_1 x_1 + h_2 x_2 + \ldots\ldots\ldots + h_t x_t) + q_1^H \overline{n} \tag{2.23}$$

$$\hat{y}_1 = x_1 + 0 + \ldots\ldots\ldots\ldots\ldots\ldots\ldots + 0 + q_1^H \overline{n}$$

So $\hat{y}_1 = x_1 + \tilde{n}$ (2.24)

$\hat{y}_2 = y - h_1 x_1$

$= (h_1 x_1 + h_2 x_2 + \ldots\ldots\ldots + h_t x_t) + \overline{n} - h_1 x_1$

$$= h_2 x_2 + h_3 x_3 + \dots\dots + h_t x_t + \bar{n} \qquad (2.25)$$

By cancelling x_1 the MIMO system is effectively reduced to $r \times (t-1)$

$$\hat{y}_2 = [\![h_2 \quad h_3 \quad \dots . h_t]\!] \begin{bmatrix} x_2 \\ x_3 \\ \vdots \\ x_t \end{bmatrix} + \bar{n} \qquad (2.26)$$

$$\hat{y}_2 = H^1 \begin{bmatrix} x_2 \\ x_3 \\ \vdots \\ x_t \end{bmatrix} + \bar{n} \qquad (2.27)$$

$$Q^1 = (H^1)^+ \qquad (2.28)$$

After that this process is repeated by decoding x_2 and so on which leads to increasing diversity order progressively through processing the scheme [39].

$\hat{y}_{t = h_t x_t + n_t}$ $r \times 1$ Channel and rth order diversity. (2.29)

Thus, schemes those are decoded later, experiencing higher diversity progressively especially if ordering applied for the zero-forcing SIC which leads to improving BER performance of the MIMO system versus noise [26] and zero-forcing success interference cancellation still uses the equation of $w_{zf} = (H^H H)^{-1} H^H$ as stated below:

The zero-forcing successive interference cancellation can be presented by:

$$\hat{x}_m = \arg\min_{s^k} |x^{(k)} - \tilde{x}_m|^2 \qquad (2.30)$$

$$\hat{y} = y - h_{k(1)} \hat{x}_{m(1)} \qquad (2.31)$$

The cancellation and ZF filtering are repeated till all symbols are detected [32].

2.10.3.2 Minimum Mean Square Error SIC Detector

For linear filtering, In MMSE detector, the background noise is considered. In order to improve performance in which also combines linear algorithm (suppressing interference) and nonlinear (serial cancellation) algorithm same as zero-forcing SIC detector. The equation of MMSE detector for interference suppression and cancellation is shown as:

$$w_{mmse} = \arg\min E[x_1 - w^H y|^2]$$

$$= (H^H H + \frac{N_0}{E_s} I)^{-1} \bar{h}_1 \qquad (2.32)$$

Where $\bar{h}_1$ is the first column vector of H^H after this hard decision is implemented to detect x_1 from: $\hat{x}_1(\text{mmse}) = w_{1,mmse} y$ (2.33)

After detecting x_1 and cancelling its effect on y then the MIMO receiver equation is:

$$y_1 = \sum_{m=2}^{M} h_m \ x_m + +\text{noise} \qquad (2.34)$$

Then the equalization is implemented to detect x_2 from the channel and cancelling its effect by MMSE SIC, then this procedure is repeated to estimate x_m and cancel its effect on MIMO system and by using this detector the performance of MIMO system increases based on SNR versus BER [32].

In order to improve diversity and performance ordering is used to mitigate the propagation of error as the MMSE_SIC performance is dependent hardly on the reliability of detected symbols in the early stages, thus a procedure of selecting the first symbol with smallest minimum square error(highest signal to interference plus noise ration) is used.

$$\{k_{(1)}, w_{k_{(1)}}\} = \arg_{k \in \{1,2,\ldots,M\}} \min \min_w E[|x_k - w^H y|^2] \qquad (2.35)$$

$k_{(1)}$ and $w_{k_{(1)}}$ are the index of the first detected symbol and its MMSE filtering vector respectively, thus the cancellation is implemented by:

$$\hat{y} = y - h_{k(1)} \hat{x}_{k(1)} \qquad (2.36)$$

Where $\hat{x}_{k(1)}$ is the $x_{k(1)}$ hard decision from $w^{H}_{k(1)}\hat{y}$. The next symbol to be detected with $\hat{y}$ is

As stated by Bai, Choi and Yu. (2014) that $(\{k_{(2)}, w_{k_{(2)}}\} = \arg\min_{k \in I} \min_{w} E[|x_k - w^{H}\hat{y}|^2]$ Where I= {1,2,……,M}\$k_{(1)}$ and \ denotes the set minus. The cancellation and MMSE filtering are repeated till all symbols are detected and by using the same procedure ordering can be implemented for Zero-forcing SIC but the equation of linear forcing is combined with successive interference cancellation instead of the MMSE linear equation[32],[40].

Chapter Three

3.1 Conclusion

In this dissertation, Massive MIMO-OFDM BER performance was simulated for frequency selective channel when different detector types were used to compare the system performance while different modulation schemes were used and the simulation results were shown by figures.

After short introduction about MIMO-OFDM technologies, a literature review was explained about MIMO system and detectors in general, secondly the theory of OFDM technology was explained and how it works briefly and some information was given about Massive MIMO system and its significance for the modern wireless communication due to its robustness for giving higher data rate within fixed bandwidth with higher transmission speed while spatial multiplexing is used and the importance of improving the spatial diversity gain by increasing the number of receiver antennas was stated. Some background theory about the communication channel was given and its effect on MIMO-OFDM system performance. The most important points in this paper, was stating some information about the advantages of combining massive MIMO with OFDM and giving some clues about different MIMO detectors supported by some references by explaining its process in removing the channel from the received signal with giving their mathematical equations.

By comparison, the concept of BER performance while different detector types were used was explained after simulation results and it was shown by simulation how BER performance improved while the modulation scheme size was decreased due to the trade-off between the spectral efficiency and error performance. Finally, the aims of this dissertation were achieved regarding MIMO-OFDM technology together and the concept of using different detector types was given for other researchers by giving a sample of Massive MIMO-OFDM wireless system through this paper. In addition of achieving the objectives of this research in simulation of BER performance by giving different scenarios and also the Matlab codes are written to guide who wants to do another research about the subject in more detail and this paper gives good indication to start PhD later.