MSc Data Telecommunication and Networks

MSc Dissertation

MIMO in Self-Optimizing Networks

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Abstract.

The aim of this study is analysing the performance of two types of MIMO channels, MIMO spatial multiplexing and MIMO spatial diversity. By understanding their characteristics, we can implement an algorithm combining them both in one system. To understand MIMO performance under different channel characteristics, we invoked on MATLAB Simulink simulation model. Two models are provided one for spatial multiplexing consisted from three major parts the MIMO antenna configuration, Turbo encoding, and the fading channel characteristics. By the same means the spatial diversity model consisted of MIMO Transmit antenna configuration, MIMO Receive antenna configuration, and the fading channel characteristics. The basic parameters that we used to check the performance of the MIMO scheme are the SNR and the correlation between transmit and receive antennas for both MIMO scheme. For each MIMO scheme, we run the provided models under different scenarios. Each scenario with different input parameters to simulate the MIMO scheme performance. The output results collected from these scenarios mainly focused on BER, Throughput, and date rate. We chose these performance parameters to make a comparison between the performance of the two MIMO schemes under different SNR and antenna correlations. From the results obtained we defined the criteria in which each MIMO scheme can provide maximum performance. We use these criteria to build an algorithm that switch between the two MIMO schemes automatically without any human intervening. This process called Self-Optimizing Network where the network element takes decision to change their MIMO configuration scheme. BER, Throughput, and SNR are the criteria where the network element takes decision to switch between the configurations. In this study, we provide in-depth analysis of the wireless channel fading characteristics and OFDM transmission with the aim of mathematical representation. Understanding the fading channel characteristic and OFDM transmission are the key factors of MIMO antenna implementation schemes. In this study, we also focused on encoding schemes used by both MIMO technique as it is impacting the performance criteria which is used to build the algorithm. Finally, from the results obtained we conclude that MIMO spatial multiplexing had high data rate with low tolerance for multipath channel fading. While MIMO spatial diversity had robustness against multipath channel fading, but the data rate is much less than that of spatial multiplexing.

Acknowledgement.

I would like to express my great thanks to all the peoples who support me during my study here in Great Britain. This study couldn't see the light without the direct instruction from my supervisor Dr Martin D. Hope many thanks for his kind support. I would also like, to thank Dr Steve Hill for his kind support to me during all the semesters that we went through. Also, my great thanks to my family for their kind encouragement and endless support especially my mother with her bless prays for my success. I would like to thank my wife for her significant support and encouragement and appreciate her patient and efforts to take care of our children during my absence. Finally many thanks to Tara, Yusuf, and Dyar my lovely kids for their tolerance and patient during my study abroad.

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Chapter 1. Introduction

1.1 Aims and Objectives.

The aim of this study is to design an algorithm based on MIMO-OFDM technology. MIMO-OFDM technology considered as an essential technology for next generation networks especially LTE networks. The advanced technology that has been used for implementing LTE networks enables LTE network elements (eNB) to interact with each other for better system performances. During the interaction the (eNBs) exchanged different update messages. To calibrate their parameters the (eNBs) used these update messages; the automated nature of this process makes the (eNBs) appears as self-optimizing network entities. Two types of MIMO-OFDM will be the object of our study, MIMO Spatial Multiplexing and MIMO Spatial Diversity. The idea is using MIMO spatial multiplexing and MIMO spatial diversity for developing an algorithm. The (eNBs) will use this algorithm to switch between the two MIMO-OFDM technologies. The switching process will be automatically without intervening from the network operator. Where the (eNBs) takes a decision on certain criteria to switch between the two MIMO technology and this process is Self-Organizing Network. To understand the rules that the (eNBs) depend on to switch between the two MIMO technologies, we must understand the characteristics and the factors that influence the process of MIMO spatial multiplexing and MIMO spatial diversity. In our study, I will give a background information about the definition of Self-Organizing Network with a brief about network design. System design is the key factor that impact the operation of MIMO technology. Our target is to use this algorithm in LTE systems, and, for that reason I dedicate one section for LTE technical overview. The propagation medium impacting the operation of MIMO-OFDM technology, understanding the medium characteristic is a crucial factor. Hence, MIMO-OFDM introduced to overcome the challenges of wireless channels. Therefore, in Chapter (2), of this study we will cover the wireless channel in details. Later we will use the information obtained from wireless channels to implement the simulation model. Also, for OFDM and MIMO, give an in-depth illustration for their operation principles, as they are forming the principal parts of the simulation model. The provided information in Chapter (2), is critical to understand the model design and specification in Chapter (3).

In Chapter (3), I will describe the main components that the MATLAB simulation model adopts to build MIMO spatial multiplexing and MIMO spatial diversity. In Chapter (3) I will introduce Turbo Coding, OFDMA, and LTE PDSCH generating in details with the aim of graphs. As they play an enormous role in the simulation model and real wireless communication system. Test and Results will be in Chapter (4); I divided the Test into two parts one for spatial multiplexing and the other for spatial diversity. Each test part have several scenarios each with different configurations and settings; the results arranged in tables with the aim of MATLAB graphs. A critical evaluation for the results will be in Chapter (5). Where the results obtained will be evaluated and listing the challenges that we face during the research implementation. Finally, I will use these results from Chapter (4) to create an algorithm that will be used in Self-Optimizing networks. The conclusion with the algorithm implementation will be in Chapter (6). Also, I included recommendations for future work in Chapter (6). All the related MATLAB codes are in a separated appendix, except for spatial multiplexing which all related MATLAB codes and Simulink model will be provide in a CD ROM.

1.2 Self-Organizing Network

Self-Organizing networks include self-configuration, self-optimization and self-healing. According to (Alexander, 2013) It is Expected to reduce human intervene to the network optimization, which reduce the capital expenditures (CAPEX) and the operation expenditures (OPEX).Self-Organizing Network (SON) become an important topic for operators rolling out modern cellular network infrastructure. Many researches and consortiums had been held recently to put a road map for implementing SON on modern cellular networks especially for LTE networks, the motivation behind that is The increased demand for high data rates for applications such as VOIP and real-time video Streaming such applications needs a reliable network with high adaptation under different network conditions, 3GPP (Release 10), ITU-T and SOCRATES which is a project consortium stand for (Self-Optimisation and self-ConfiguRATion in wirelEss networkS) had been involved in releasing standards and requirements for SON. The LTE advance new standards demands for more than 1Gbps for low mobility and more than 100Mbps for high mobility to support different mobile application in a very high data rates. According to (Zarrinkoub, 2012) this become possible because of the following:

1. The integration of enabling technologies with sophisticated mathematical algorithm such as, OFDM, MIMO, and Turbo Coding.
2. The process or how to use the network resources and bandwidth efficiently such as using, Adaptive Modulation, Adaptive Coding, Adaptive MIMO, and Adaptive Bandwidth

The idea of SON is to adjust the network parameters accordingly upon the changes happening To the network without been noticed by the network subscribers, all the adjustments are done Automatically by running background algorithms to measure the up-to-date network condition, and sending update messages to all network elements to recalibrate their parameters, functions to the new conditions, this can be achieved by monitoring the network on periodical intervals. For certain parameters related to network performance such as BER, throughput, capacity, etc. It is very important for network operators to provide a firm radio planning that ensure suitably Dimensioning for their radio network to overcome unexpected situations. And this includes Coverage dimensioning, Capacity dimensioning, Active user dimensioning and Interface dimensioning. Interface dimensioning is an important factor for LTE networks, where all the traffics and update Messages are going through these interfaces.

Where S1 interface connects the radio access elements (eNBs) back to the core network (EPC), and X2 interface used to exchange update messages among the eNBs. In reality, both interfaces share the same transmission path but they are separated in the physical layer interface. According to (Huawei Technologies Co., 2010) Figure (1) shows the main process of radio network planning.

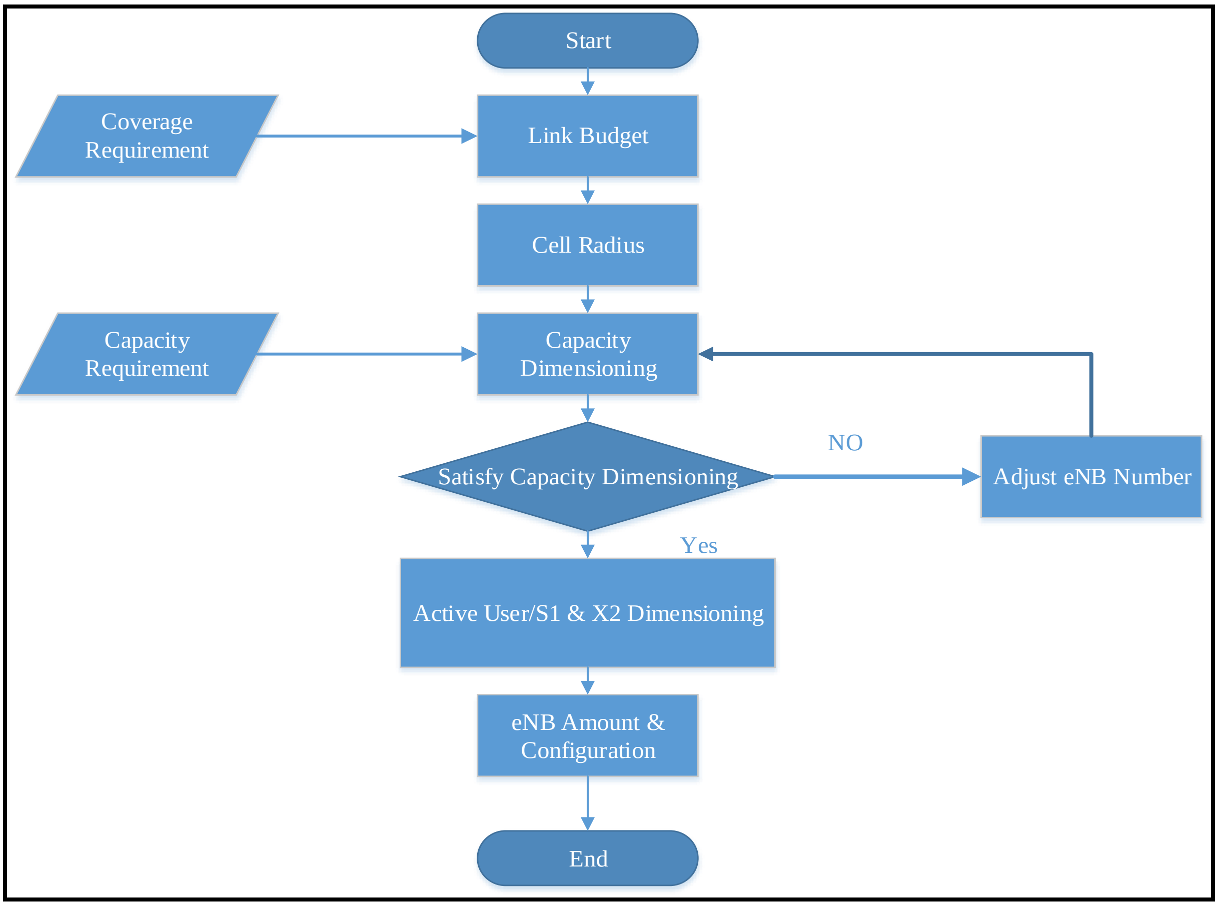


Figure 1: Radio Network Dimensioning Flow (Huawei Technologies Co., 2010)

The mentioned information are essential for SON architecture; SON had three types
Of architectures depending on the radio network planning and dimensions:

1. Distributed SON, The SON functions distribute among the network elements especially (eNBs), where localization decisions can be made by them (eNBs).
2. Centralized SON, where functions are closer to the core network (EPC), where in this Type of architecture the core network can have a broader view of different network entities and made coordination among them.
3. Hybrid SON, where it is a mix of distributed and centralized architecture.

1.3 LTE Technical Overview

According to (3GPP,Rel.10, 2013) LTE system consist mainly from two parts the evolved Universal Terrestrial Radio Access Network (eUTRAN) and the evolved Packet Core (ePC). The (eUTRAN) consist of eNBs that are responsible for providing the radio access to the UE. On another hand the ePC consists of the Mobility Management Entity (MME), Packet Gateway (P-GW) and the Serving Gateway (S-GW), in practical most of the functionality of ePC are done through the MME.

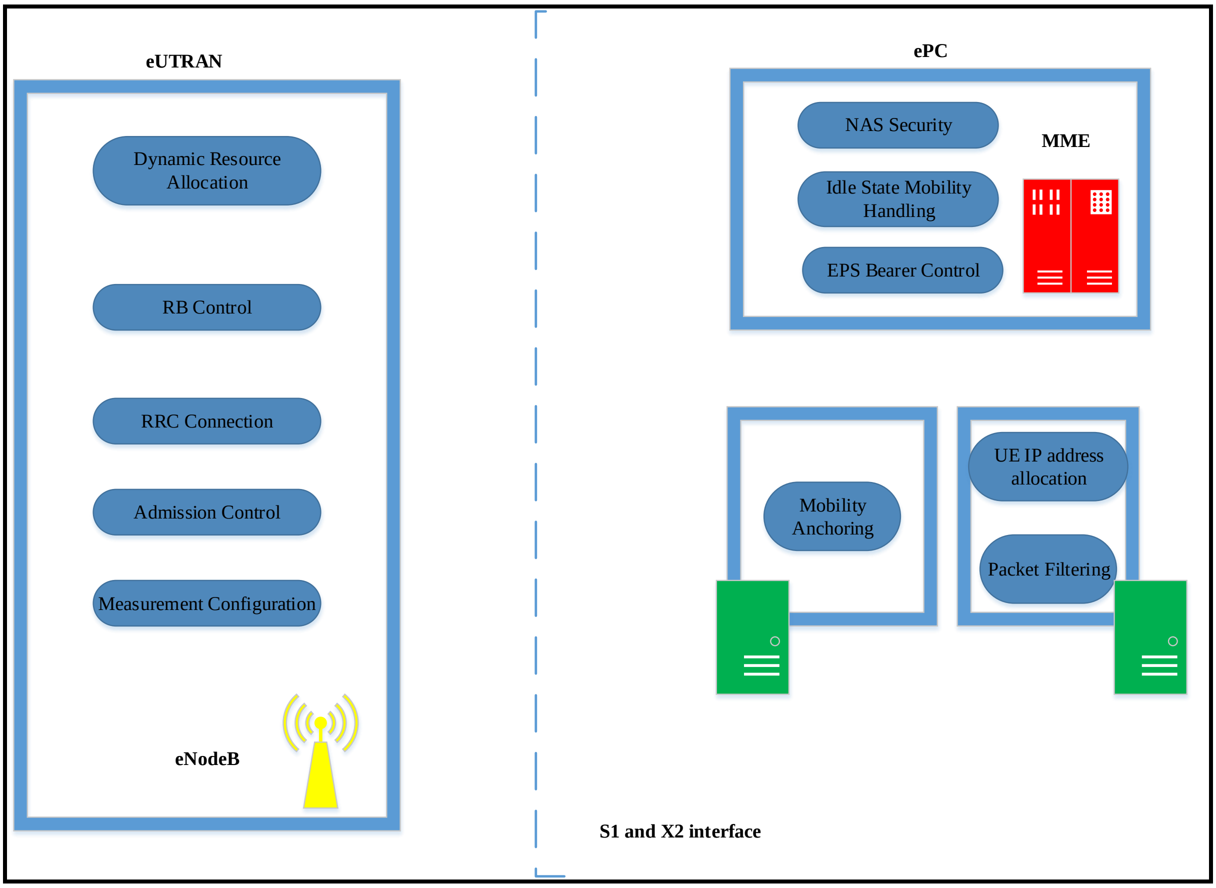


Figure 2: LTE System Diagram (Alcatel-Lucent, 2012)

The main functions of eNB according to (3GPP,Rel.10, 2013) is:

1. Schedules the user traffic each 1 ms. in DL and UL taking in account the QoS that associated with the data.
2. Control the creation, modification and release of the radio bearers.
3. Handles the RRC connection for each UE.
4. Performs admission control to avoid an overloaded number of users.
5. Configure the UE measurements on the adjacent cell for the handover process.

The main functions of the ePC issued by (3GPP, Rel.10, 2013) is:

a. Non Access Stratum (NAS) signalling and (NAS) signalling security.
b. NAS security control.
c. Inter core network node signalling for mobility between 3GPP access networks.
d. Idle mode UE reachability including control and execution of paging retransmission also tracking area list management for UE in idle or active mode.
e. PDN gateway and serving gateway selection, MME selection for handover with MME change, SGSN selection for handovers to 2G and 3G access network.
f. Roaming and Authentication.
g. Bearer management function including dedicated bearer establishment.

It is important to understand the LTE-Uu radio interface and the associated channels between different LTE layers as one of these channels will be the base of our test implementation, the diagram below depicting LTE radio layers and channels.

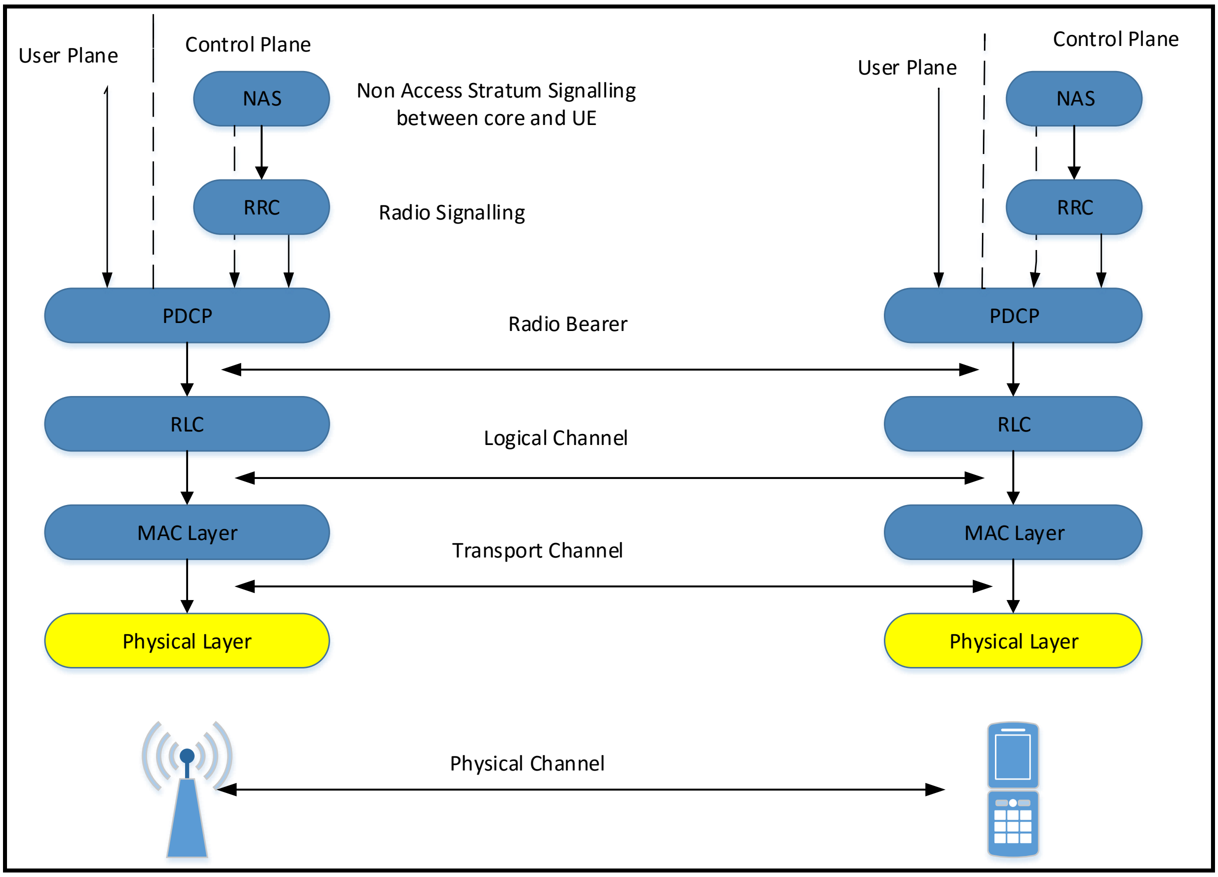


Figure 3: LTE Radio Layer (Alcatel-Lucent, 2012)

- **Physical (PHY) Sublayer:** the physical layer is between the UE and the eNB. The layer in LTE supports the ARQ with soft combining, uplink power control and multi-stream transmission and reception (MIMO).
- **Media Access Control (MAC) Sublayer;** the MAC sublayer is between the UE and the eNB.it performs error correction through HARQ, priority handling across UEs as well as across different logical channels, traffic volume measurement report, multiplexing/demultiplexing of different RLC sublayer.
- **Radio Link Control (RLC) Sublayer:** the RLC is between the UE and the eNB. The RLC dose error correction through the ARQ, in-sequence delivery of upper layer PDUs, duplicate detection, and flow control with concatenation /re-assembly of packets.
- **Packet Data Convergence Protocol (PDCP) Sublayer:** for the user plane the PDCP sublayer performs header compression and ciphering.
- **Radio Resource Control (RRC) Sublayer:** the RRC is between the UE and the eNB. The RRC sublayer in essence performs broadcasting, paging, connection management, radio bearer control, mobility function and UE measurement reporting and control.
- **Non Access Stratum (NAS) Sublayer:** the NAS is between the UE and the Mobility Management Entity (MME). It performs authentication, security control, idle mobility handling, and idle mode paging origination.

It is important also, to understand the channels associated with each sublayer, where each sublayer channels are mapped (encapsulated) into the under sublayer channels from the upper layers to the physical layer and de-mapped in the opposite direction. We had the following channels from the upper layer to the physical layer according to (Alcatel-Lucent, 2012):

<u>Transport Channel:</u>

- PCH: Paging Channel.
- BCH: Broadcast Channel.
- MCH: Multicast Channel.
- DL-SCH: Downlink Shared Channel.
- UL-SCH: Uplink Shared Channel.

Logical Channel:

- PCCH: Paging Control Channel.
- BCCH: Broadcast Control Channel.
- CCCH: Common Control Channel.
- DCCH: Dedicated Control Channel.
- MCCH: Multicast Control Channel.
- MTCH: Multicast Traffic Channel.

Physical Channel: (here I will list the channels that's much related to my project).

- PDSCH: Physical Down-Link Shared Channel.
- PUSCH: Physical Up-Link Shared Channel.
- PBCH: Physical Broadcast Channel.
- PRACH: Physical Radio Access Channel.
- PMCH: Physical Multicast Channel.

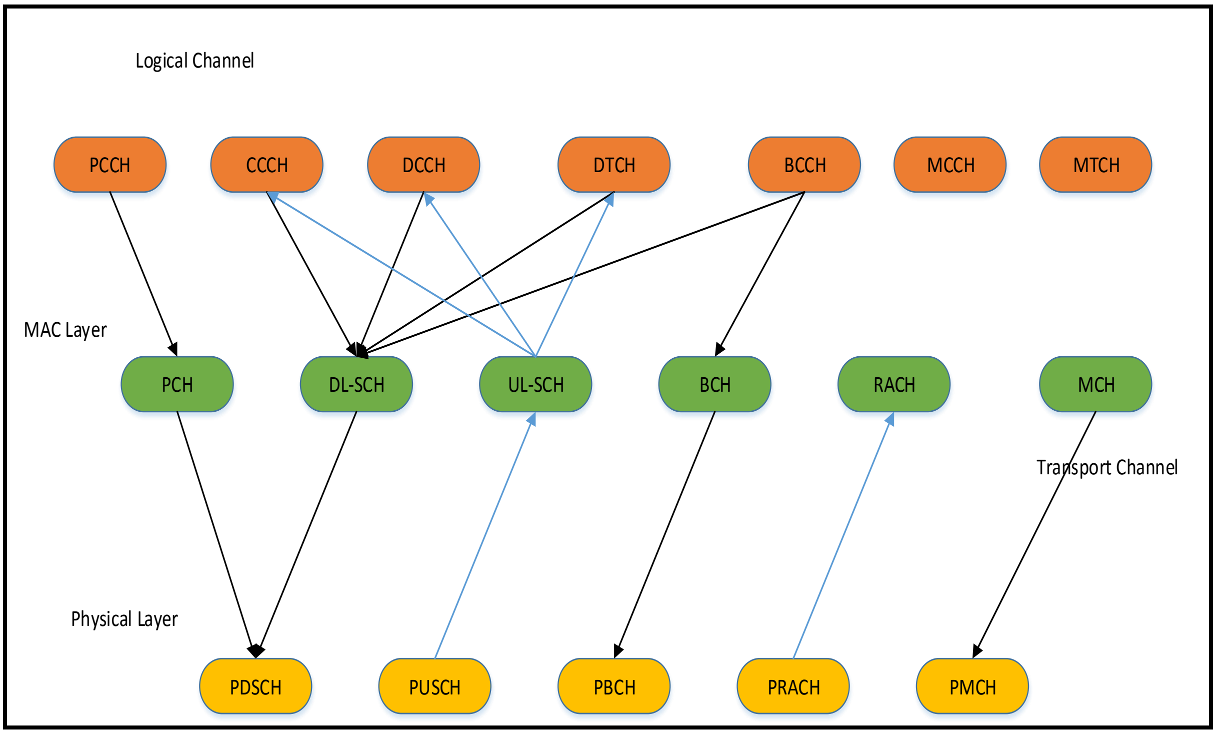


Figure 4: LTE Sublayer Channels (Alcatel-Lucent, 2012)

The LTE PDSCH will be used as a material to test the MIMO performance through, so it was important to understand the hierarchy of different sublayer channels and how they are mapped from the upper layer down to the physical layer.

Chapter 2 (Wireless Channel)

2.1 Classification of Fading

According to (Cho, et al, 2010). The performance of any wireless communication channel is much related (limited) by the surrounding environment. Unlike wired and fibre communication channels where the channel characteristic is static and predictable, the wireless channel is variable function of time and surrounding environment, in another word it is unpredictable. The recent demands for more data rate made the optimization of a wireless channel a mandatory issue and a big challenge in the same time, especially when we talk about 1Gbps data rate like LTE advance. It is necessary to understand the types of fading that is associate with wireless communication. Understanding fading will help to understand the technologies and researches that have been adopted to overcome fading. In general the electromagnetic waves generated by the wireless communication channel share some properties with light. As the light ray, the electromagnetic wave is subject to Reflection, Diffraction and Scattering (Rappaport, 2002), (Sklar, 2013). Reflection occurs when the incident wavelength on an object is much smaller than the object dimensions, where $\lambda=c/f$. Reflection is an important physical phenomenon where the signal is reflected back to the transmitter (it is an important parameter for wired and wireless communication and especially in waveguides and fibre optics). Diffraction occurs when the transmission path between the transmitter and the receiver is obstructed by surfaces with sharp irregularities or with small opening. That will force the wave to bend around and to spread out of the small openings, the spreading wave can be useful for Non-Line-of-Sight communication. Scattering in the other hand occurs when the electromagnetic wavelength is much greater than the object dimensions which force the wave to deviate from its path. The other important phenomenon in wireless communication channel is “Fading” where the amplitude of the propagation signal vary as a function of frequency and time. Fading can extremely effect the operation of wireless system (Volakis, 2007). It is another source of signal degradation, and it is characterized as a non-additive signal disturbance in the communication channel. Signal disturbance is caused by Multi-Path effect where the receiver received the same copy of the transmitted signal at different time, understanding fading phenomenon is an important factor to overcome the limitations of wireless channels for obtaining high data rate transmission and high throughput. Figure (5) shows the classification of Fading Channels.

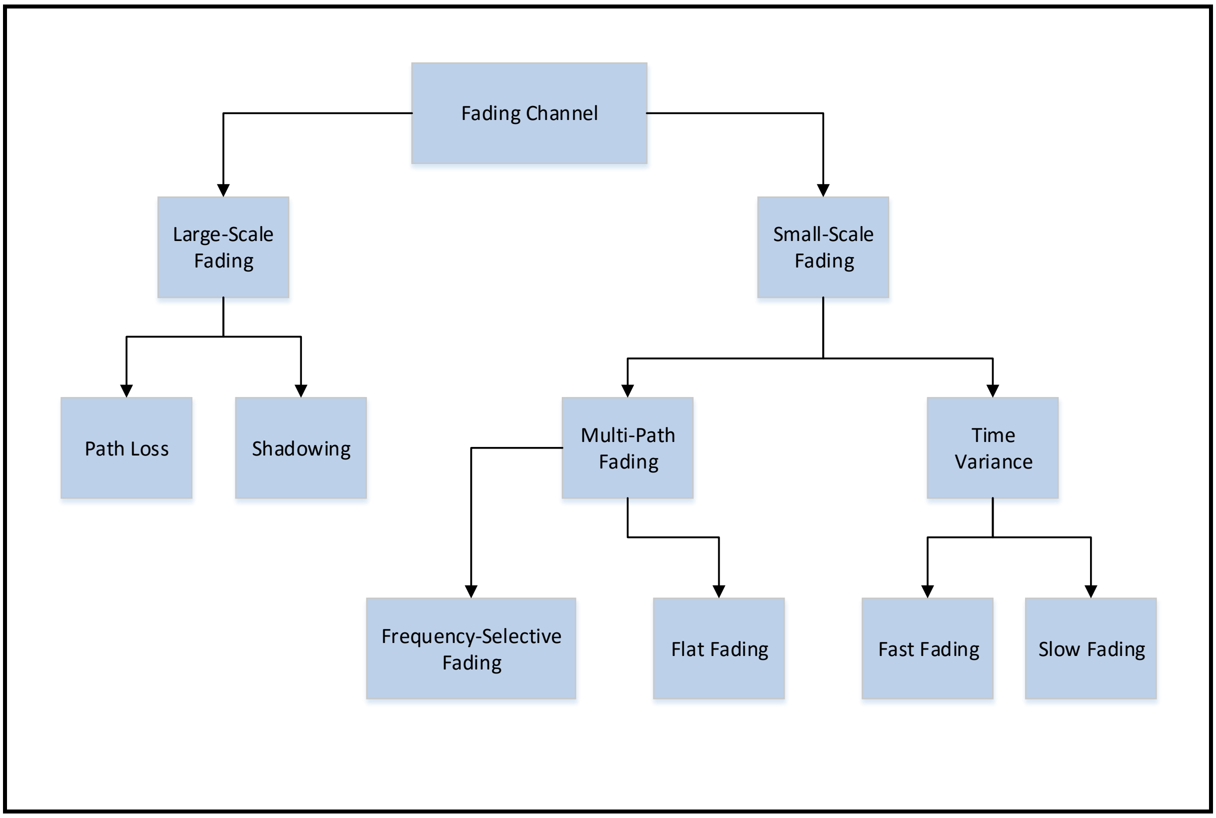


Figure 5: Classification of Fading Channels (Cho, et al, 2010)

Fading channel can be classified into Large-Scale Fading and Small-Scale Fading. Large-Scale fading occurs due to the distance between the transmitter and the receiver where the path loss increases as the distance increased where different obstacles are subjected to the signal propagation like buildings, trees, terrains…etc. Where these obstacles cause shadowing fading effect; hence, large-scale fading function of distance and shadowing.

Small-Scale Fading is the sudden fluctuation of the signal amplitude due to the multipath interferences where sometimes these interferences increase the signal level and sometimes decreasing it; this occurs due to short distance movement of the mobile station (UE). According to the size of multipath, the frequency selectivity of the channel can be characterized to frequency – selectivity or frequency flat, and from the time variation due to the mobile speed we can determine whether the channel characteristic is fast-fading or slow fading, (Doppler effect).If we recall the flow-chart for network dimensioning in Chapter one. We can see that to determine the coverage of the network or the signal strength between the transmitter and receiver we must implement Link Budget. Link Budget is a crucial tool for implementing radio communication system, it allows as to predict the signal strength at the receiver. Two important factors must be taken in our consideration in link budget, path loss and fading.

The path loss is deterministic as it is a function of the distance (large-scale fading). While shadowing and small-scale fading are random, and their effects can only predict by their probability distribution. So to determine the targeted receive signal level we must add some margin to the link budget to insure the correct received signal. The challenge is to determine how much margin we must add to our link budget design that insure correct received signal level. In this section, I will take one example for large scale fading model and another example for small scale model by using MATLAB program.

2.1.1 Large-Scale Fading Channel.

Many models had been introduced to calculate the path loss between the transmitter and the receiver. The most popular one is the Okumura path loss model where it was obtained through extensive on field experiments to calculate the path loss associated with different antenna heights. For both the transmitters and receivers. And different frequency range [500-1500 MHz] and Different cell size [1-100Km], this model helps to predict path loss in an urban area, yet this model is not covering other kinds of terrains, such as suburban area and open area, so this model had been extended to a new model called Hata model which covers suburban and open areas terrains the new model is based on Okumura model and it is a popular model used till now for different mobile communication networks. Although the Hata model covers different types of terrain, but the range of frequency is still between [500-1500MHz], the most reliable model which is run on the log-normal of the shadowing path loss is the IEEE 802.16d.Where the path loss measurement around the cell is random and follow a log-norm distribution (D.C.Cox, et al, 1983). The model was first introduced for wireless metropolitan area networks like (WiMax). In this model range of frequency extended beyond Okumura/Hata model. And this made IEEE 802.16d more suitable for calculating path loss for nowadays 4G networks where the recommendation and standards ask for more bandwidth that can be obtained by using higher carrier frequencies, such us 2.6GHz for LTE advanced. According to (IEEE, 802-16j, 2007-02-19). The channel model had three different types of model depending on the density of obstructions between the transmitter and the receiver, the model types are (type A, B and C). Table (1) lists these types.

Type	Description
A	ART to BRT hilly terrain with moderate to heavy tree density
B	ART to BRT intermediate path loss condition
C	ART to BRT for flat terrain

Table 1: IEEE 802.16d Path Loss Model Types (IEEE, 802-16j, 2007-02-19)

Where, ART stand for Above-Roof-Top and BRT stand for Below-Roof-Top.

According to (IEEE, 802-16j, 2007-02-19) The IEEE 802.16d path loss model is given by:

$$PL_{M802.16}(d)[dB] = \begin{cases} 20log_{10}\left(\frac{4\pi d}{\lambda}\right) & for\ d \leq d_\circ' \\ 20log_{10}\left(\frac{4\pi d_\circ'}{\lambda}\right) + 10\gamma log_{10}\left(\frac{d}{d_\circ}\right) + C_f + C_{RX} & for\ d > d_\circ' \end{cases} \quad \ldots\ldots (2.1)$$

Where $d_\circ = 100m$ and $\gamma = a - bh_{Tx} + c/h_{Tx}$ where a, b and c are constant that is changed according to the model type if it is A, B or C.

The carrier frequency is given by $C_f = 6log_{10}\left(\frac{f_c}{2000}\right)$ .... (2.2)

The correlation coefficient is given by $C_{RX} = \begin{cases} -10.8log_{10}\left(\frac{h_{Rx}}{2}\right) for\ Type\ And\ B \\ -20\ log_{10}\left(\frac{h_{Rx}}{2}\right) for\ Type\ C \end{cases}$ ...... (2.3)

Finally $d_\circ' = d_\circ 10^{-(C_f+C_{RX})/10\gamma}$ where it is the new reference distance to prevent discontinuity at the distance of 100m.Figure (6) shows path loss model for IEEE802.16d for 2.6GHz carrier frequency based on Okumura path loss model and type ‘A’ terrain environment.

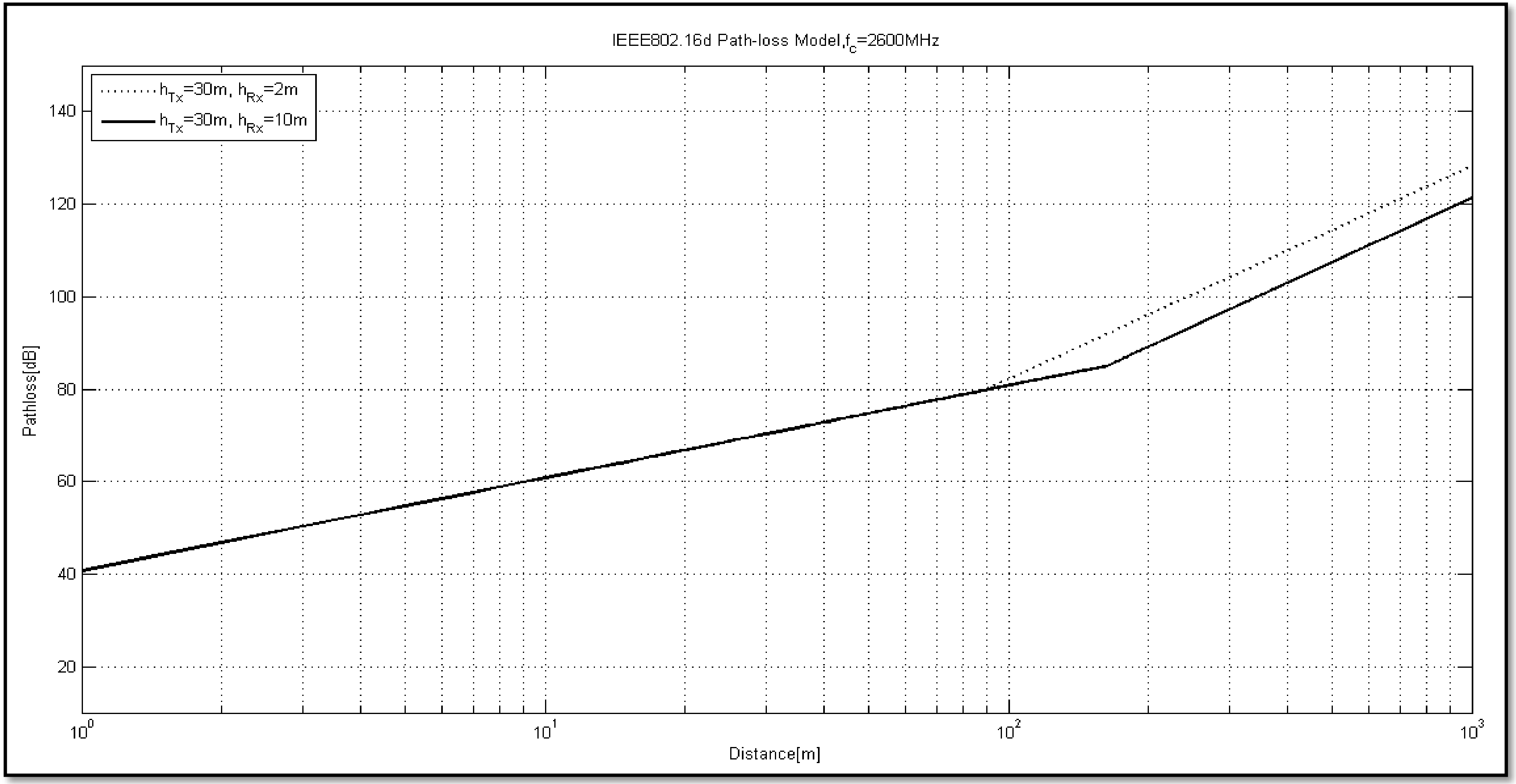


Figure 6: IEEE802.16d Path Loss Model **(Cho, et al, 2010)**

Figure (6) shows the path loss as a function of distances and antenna height, the relation between path loss and distance is proportional as the distance increased the path loss increased too. While the relation is inversely proportional with the antenna height, as the antenna height decreasing the path loss increased. And we can observe from Figure (6) that as we reduce the receiver antenna height the path loss increased.

2.1.2 Small-Scale Fading Channel.

According to (Cho, et al, 2010), Small-Scale fading defined as the rapid change in the signal level due to the movement of the received terminal (UE). This rapid change is caused by the multiple signal paths. Interferences occur when multiple copies of the same signal arrived at the receiver antenna at different times. Hence, if they are at the same phase the received signal is high and if they are out of phase the signal level is low (Hourani, 2004/2005). Due to that the received signal level fluctuated at the receiver. Four factors can characterize small-scale fading, multipath propagation, terminal speed (UE), speed of surrounding objects and the transmission signal bandwidth. To characterize small-scale fading channel, there are some important parameters to identify. Like the Power Delay Profile (PDP), the (PDP) is characterized by the relative delay and the average power of different multiple fading paths. The relative delay is the overindulgence delay with respect to reference time (usually the first received signal tap time). While the average power is normalized by that of the first path received (usually the line-of-sight first path or tap). The mean of the multipath overindulgence delay and the root mean square (RMS) delay spread are important factors to provide bases for different multipath fading channels comparison. It is important to calculate the overindulgent delay so we can calculate the RMS delay spread which is a very important for understanding the channel coherence bandwidth.

$$\bar{\tau} = \frac{\sum_i v_i^2 \tau_i}{\sum_i v_i^2} = \frac{\sum_i \tau_i P(\tau_i)}{\sum_i P(\tau_i)} \text{ .... (2.4)}$$

Where $\bar{\tau}$ is the mean of the overindulgent delay, and τ_i is the channel delay of the *i*th path while v_i is the amplitude (in volte), and $P(\tau_i)$ is the power. From above we can now calculate the RMS delay spread which is taken from the second central moment of the PDP.

Let σ_τ be the RMS delay spread of the second central moment of the PDP then,

$$\sigma_\tau = \sqrt{\overline{\tau^2} - (\bar{\tau})^2} \quad \text{.... (2.5)} \quad \text{Where} \quad \overline{\tau^2} = \frac{\sum_i \tau_i^2 P(\tau_i)}{\sum_i P(\tau_i)} \text{.......... (2.6)}$$

The coherence bandwidth which is the maximum bandwidth in which two frequencies of the signal experiences correlated amplitude fading, the coherence bandwidth (B_c) is inversely proportional to the RMS delay spread.

$$B_c \approx 1/\sigma_\tau \quad \text{..................... (2.7)}$$

Equation (2.7) gives us an understanding regarding the fading channel whether the channel is Frequency-Selective Fading channel or Time-Selective Fading channel. Frequency-Selective Fading is due to the time dispersion fading, where the transmitted signal may subject to fading in the frequency domain either selective or non-selective manner. The channel considered as frequency-non-selective fading if:

$$B_s \ll B_C \;\; and \;\; T_s \gg \sigma_\tau \quad \text{........................ (2.8)}$$

Where $B_s \; and \; T_s$ are the bandwidth and symbol period of the transmitted signal, while $B_c \; and \; \sigma_\tau$ are the coherence bandwidth and RMS delay spread, respectively. In the same time the channel is considered to be frequency-selective channel if:

$$B_s > B_c \;\; and \;\; T_s \ll \sigma_\tau \quad \text{........................ (2.9)}$$

The above information is essential for modelling wireless communication channel especially when we talking about high data rates. In the frequency-selective case the transmitted signal is subjected to frequency-selective fading when the channel had a constant amplitude and linear phase with bandwidth less (narrower) than the transmitted signal bandwidth. In this case multiple copies of the transmitted signal will overlapping at the receiver causing Inter-Symbol Interference (ISI) that impact the throughput of the wireless communication system.

Time-Selective Fading channel in the other hand is due to frequency dispersion and it is much related to the mobility speed of the mobile terminal (UE). In which induces a phenomenon called Doppler Effect or Doppler spread, this phenomenon causes either fast or slow fading. Where in fast fading and due to the movement of the mobile terminal causes the channel impulse response varies rapidly. This rapid variation is in the time domain causes shifting in the frequency domain. The amount of shift in the frequency domain is called Doppler Shift. If the Doppler shift frequency is f_s then the Doppler bandwidth $B_d = 2f_s$ and the coherence time associated with the channel inversely-proportional to Doppler shift frequency, if T_c represent the coherence time then:

$$T_c \approx 1/f_s \quad \text{……………..} \; (2.10)$$

According to (ITU-R M.1225, 1997) the channel considered as a fast fading channel if $T_s > T_c$ and $B_s < B_d$, where $T_s \; and \; B_s$ are the transmitted symbol time and bandwidth, respectively. The channel is considered as a slow fading channel when $T_s \ll T_c \; and \; B_s \gg B_d$, where in this case the channel impulse response is varying slowly (static channel). In wireless communication the signal propagation in any environment (Indoor or Outdoor) is either Line-OF-Sight (LOS) or Non-Line-OF-Sight (NLOS). The probability density function of the received signal in (LOS) propagation follows Rician distribution and for (NLOS) is Rayleigh distribution. These two types of distribution that is associated with the signal propagation is crucial for implementing and modelling MIMO channels as we will see in the next chapters. The fact that the received signal in a wireless channel can be understood as a sum of multiple received scattered signals and these received signals are randomly arrived to the receiver (random time, random amplitude, random angle of arrival…etc.), these random components of the propagated signal can be represented as a complex Gaussian random variable (CLARKE, 1968). However, the number of the signal scattered component is infinite and they are Independent-Identically-Distributed (IID) with mean (μ) of zero and variance of (σ^2). In (NLOS) environment let X represent the amplitude of complex Rayleigh Gaussian random variable, where $X = \sqrt{W_1^2 + W_2^2}$, where $W_1 \; and \; W_2$ are the Gaussian random variables, then the probability density function for Rayleigh fading channel is given by:

$$f_x(x) = \frac{x}{\sigma^2} \, e^{-\frac{x^2}{2\sigma^2}} \text{…………………} \; (2.11)$$

Where $2\sigma^2 = E\{X^2\}$ and X^2 is the chi-square of the random variable. For (LOS) signal propagation, the environment is much more lenient than of (NLOS). Where the signal is not subjected to reflection, scattering and detractions as it travels through the channel, as we mentioned earlier the (LOS) propagation is following Rician distribution, and for this kind of distribution the amplitude of the received signal can be expressed as:

$X = c + W_1 + jW_2$, the only different with that of Rayleigh distribution is the LOS component (c), while for $W_1\ and\ W_2$ are the (IID) Gaussian random variables with mean (μ) of zero and variance of (σ^2), just like the (NLOS) distribution. The Rician PDF is given as:

$$f_x\,(X) = \frac{x}{\sigma^2} e^{-\frac{x^2+c^2}{2\sigma^2}} J_\alpha(xc/\sigma^2) \text{............ (2.12)}$$

Where J_α is the Bessel function of the first kind, which is a solution of a differential equation that is finite at the origin (at X=0). Last thing to be mentioned regarding Rician distribution is the Rician K-factor, where it be used when there is an LOS component. This is mean that the first path arrived with any reflection can be considered as Rician fading component.

$$K = \frac{c^2}{2\sigma^2} \text{ .... (2.13)}$$

Where K-factor is the ratio between the specular components power c^2 which is a scattered component but with higher power (amplitude) compared with the other scattered components ($2\sigma^2$). So in this case they will be considered as Rician fading component not Rayleigh fading component (Jargen Bach Andersen, Theodore S. Rappaport, and Susumu Yoshida, 1995).

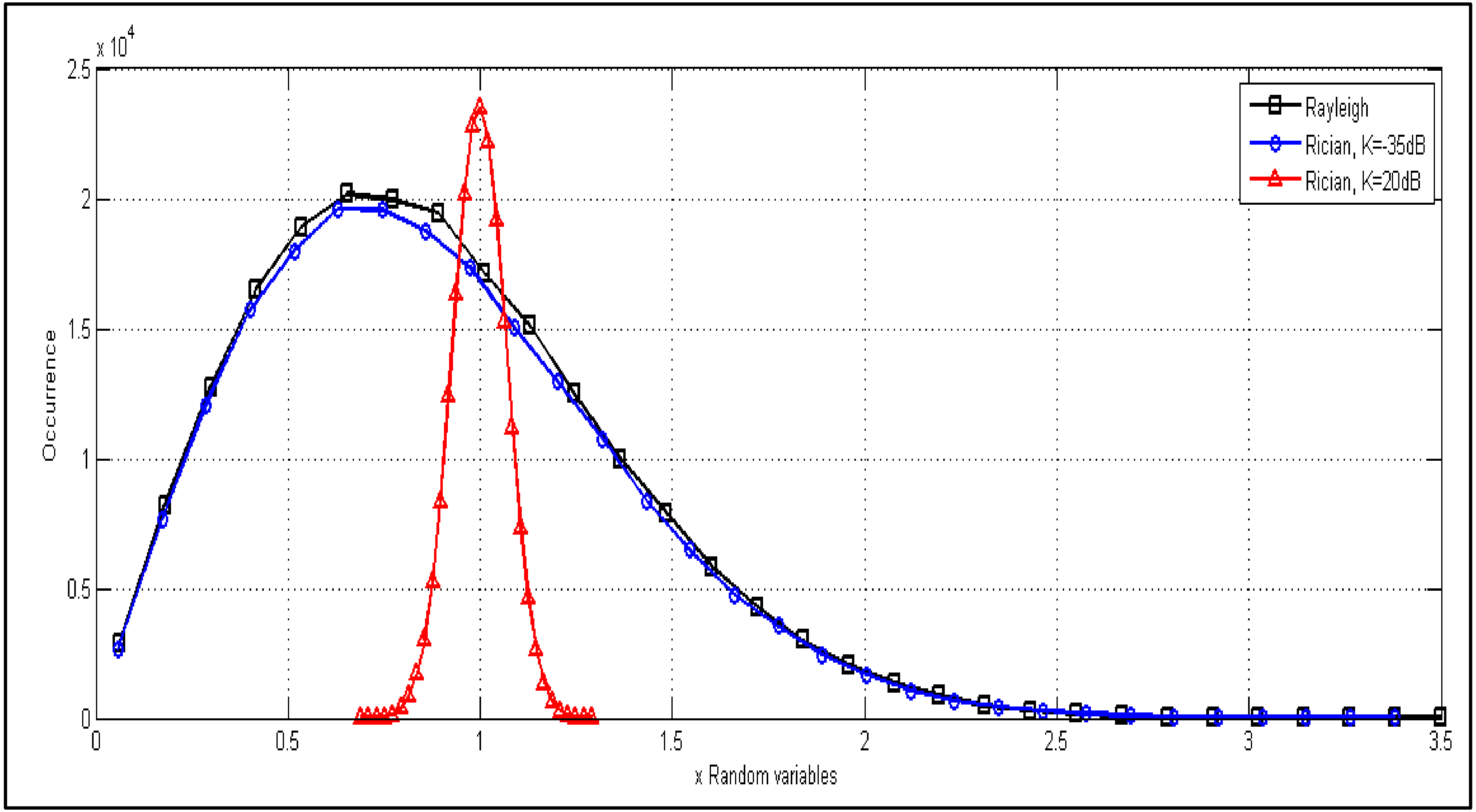


Figure 7: Rayleigh and Rician Distribution Fading (Cho, et al, 2010)

2.2 Orthogonal Frequency Division and Multiplexing (OFDM) Concepts.

According to (Wong, 2012) orthogonal frequency-division multiplexing (OFDM) is not a new idea for wireless communication transmission, it had been introduced around 1985 by Cimini, but the fundamental of OFDM had been introduced even earlier. Nowadays it becomes an ordinary fact for new wireless standards and systems; LTE advance, for example, uses OFDM as its air interface to achieve high transmission performance.

As we discussed in (Section 2.1) we run into frequency-selective fading when the channel RMS delay spread (σ_τ) is much larger than the symbol period (T_s), or we just say $\sigma_\tau \gg T_s$.

We cannot change the RMS delay spread as it is much related to the environment where the signal is propagate, but we had control over the symbol period (rate).According to (Bingham, 1990) higher data rates transmission can be achieved with multi-carrier. However, Symbol rate is related to the modulation scheme and for ordinary single carrier transmission we need this period as small as possible so we could achieve higher data rates, yet this will not solve the problem of frequency-selective fading to overcome the delay spread. OFDM introduces a solution for transmission signals at high data rates, and this achieved by transmitting a signal over N multiple parallel channels. Where each channel transmit at a rate of (D_r/N), and D_r is the data rate and N is the number of multiple parallel channels. Where each of these channels is running on a low rate, and it forms the OFDM subcarriers that combined to produce the targeted data rate. (Wong, 2012) Pointed out that OFDM had the following advantages:

- Provide compact spacing between the subcarriers to prevent losing orthogonality.
- With the help of digital signal processing, we can reduce the cost associated with building, modulation/demodulation for each subcarrier, filters, oscillators…etc. by the digital signal processing we can implement DFT and IDFT with one baseband filter and one carrier frequency on the transmitter side, and using one coherent demodulator in the receiver side, just like ordinary single carrier system.
- The IDFT and the DFT can be implemented through IFFT and FFT.
- OFDM had Cyclic Prefix, which reduce the effects of multipath delay spread more.

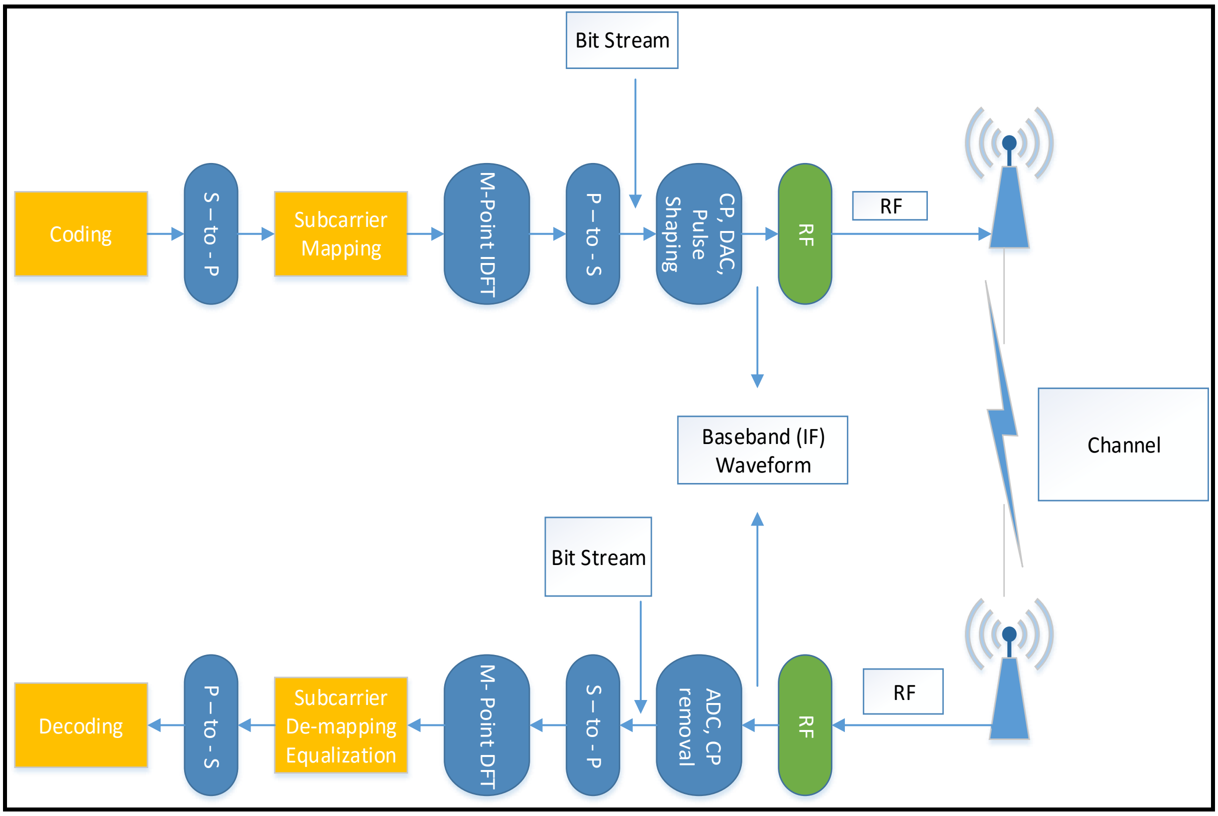


Figure 8: OFDM Block Diagram (Wong, 2012)

Figure (8) shows OFDM principal components, and as we mentioned earlier that the OFDM signal is consisted from N subcarriers, so it is important that these subcarriers maintain spacing between themselves so that orthogonality maintain, the minimum spacing between subcarriers to maintain orthogonality is ($1/NT_s$). Orthogonality between the subcarriers can be checked through the implemented DFT in the digital signal processor, where (B.P.Lathi, 2005) claims that two signals are considered to be orthogonal if their inner (scalar or dot) product is equal to zero over given an interval.

$$\int_{t_1}^{t_1} x(t)y(t)dt = 0 \quad \text{Over the interval } [t_1 , t_2] \ldots\ldots\ldots\ldots (2.14)$$

The general OFDM equation over the period $0 \le t \le NT_s$ is given by:

$$x(t) = \sum_{n=0}^{N-1} X_n \Pi\left(\frac{t - T_s'/2}{T_s'}\right) exp\left(j2\pi \frac{nt}{NT_s}\right) \ldots\ldots\ldots\ldots\ldots\ldots (2.15)$$

Where ∏ is a rectangular function. T_s' Is equal to the number of subcarriers *N* multiplied by the symbol period plus the *Cyclic Prefix* (Ove Edfors, et al, 1996). In which added to the guard time between the subcarriers. Hence, we get two advantages one is to mitigate the frequency-selective fading and secondly to makes the entire transmission appear as a part of cyclic transmission.

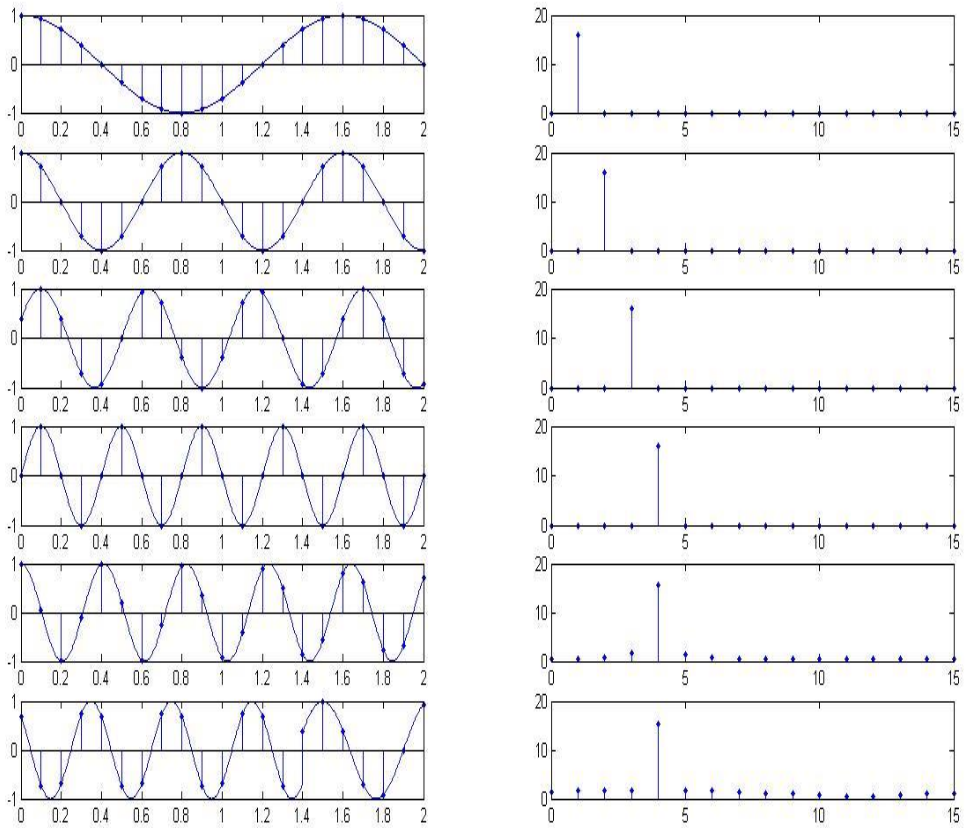


Figure 9: Orthogonality of Different Sinusoid Signals (Cho, et al, 2010)

To appreciate the virtue of OFDM to mitigate channel fading especially Rayleigh effect that is a regular channel fading in NLOS. Figure (10) and (11), shows a comparison between two fading channel one without OFDM equalizer and the other with OFDM equalizer implemented, this simulation done with Monte Carlo simulation provided by MATLAB.

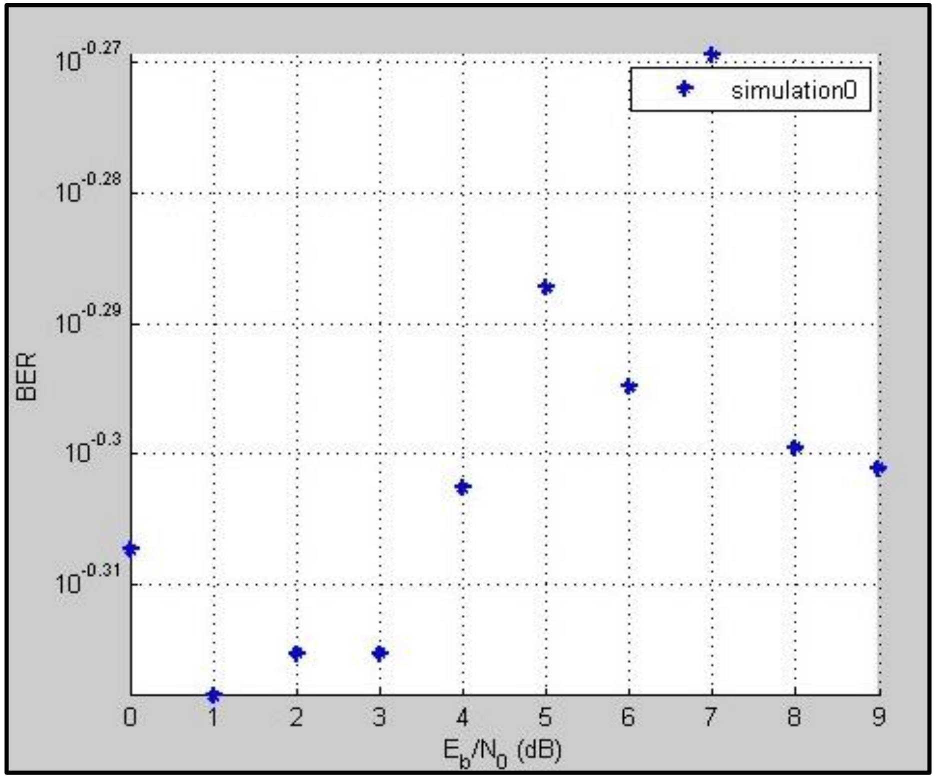


Figure 10 Rayleigh Fading without Equalizer (Cho, et al, 2010)

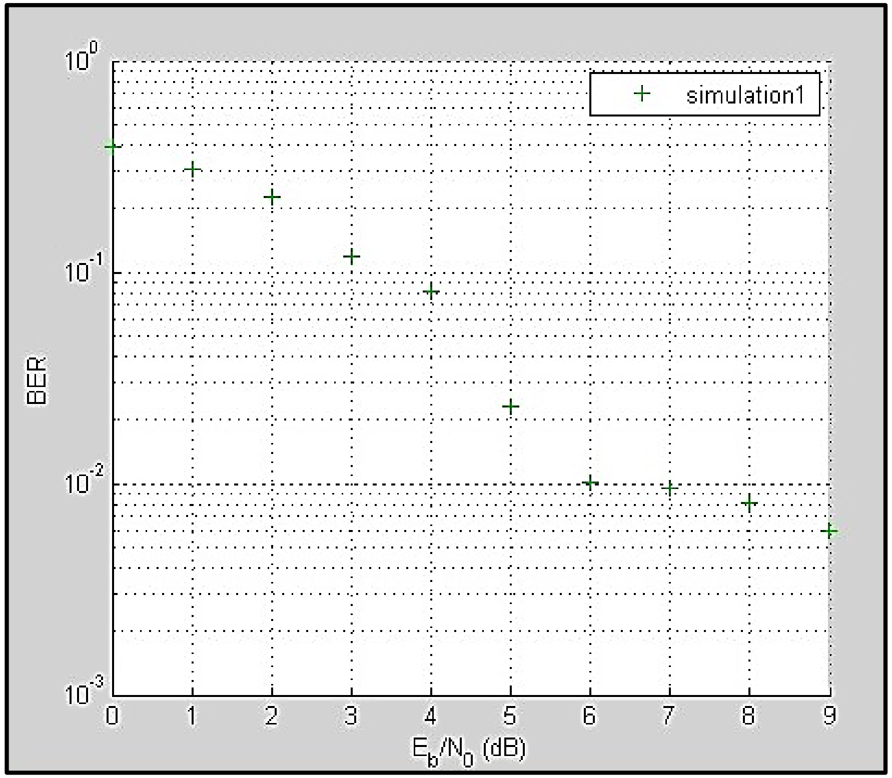


Figure 11 Rayleigh Fading with OFDM Equalizer (Cho, et al, 2010)

As we can see from Figure (10).When multipath fading is high, the performance of BER, will deteriorate. So we need to add an equalizer in the receiver side to correct the effects of the Rayleigh fading. Figure (11) shows clearly that OFDM had mitigated the Rayleigh Fading effects. OFDM robustness against fading makes it the premier access method for LTE radio networks. (3GPP TR 25.892 , 2004). Also, in the later chapters we will use OFDM as the access method for the simulation model.

2.3 Multiple-Antenna Techniques [MIMO].

Since the late of 1990s, there has been a lot of researches and developments in multiple-antenna technology; the researchers introduced new terms for wireless communication industry, like multiple inputs, multiple outputs (MIMO), transmit diversity, space-time coding, spatial multiplexing, Alamouti scheme…etc. Implementing multiple antennas on both transmitter side, and receiver side gave the system extra gain primarily to mitigate the channel fading and increasing the throughput, hence increasing the system overall performance. (Wong, 2012) Claims that multiple antenna techniques can be classified into four types:

1. Spatial multiplexing: used to increase the data rate by transmitting multiple independent data streams simultaneously.
2. Spatial diversity: used in low SNR communication medium to increase the system performance through implementing space-time coding, antenna diversity…etc.
3. Smart antenna: also known as adaptive antenna arrays, where it improve the SNR and reducing the co-channel interference.
4. Hybrid techniques: in which uses two or more of the above technique.

For our project, we are appealing in Hybrid technique, where we use spatial multiplexing and spatial diversity (Antenna Diversity) on the same system. However, both MIMO technique are an antenna array transmission (Daniel W. Bliss, et al, 2005). For that we will make comparison between the two techniques under different channel condition (SNR, BER, and Throughput).

2.3.1 MIMO Spatial Multiplexing.

(ITU-R, 1997) Defines that the aim of spatial multiplexing is to increase the data rates. Basically, if we had m-by-n transmit and received antennas respectively, then we have m different channels that we can transmit our data over it, and each of these m channel paths can carry out different data stream. And by this we increased the data rate of the communication system, and the system capacity increased linearly with increasing m and n. However, things are not so easy, where finding statistically independent channels between the transmitter, and the receiver is not all the time supporting such an ideal case.

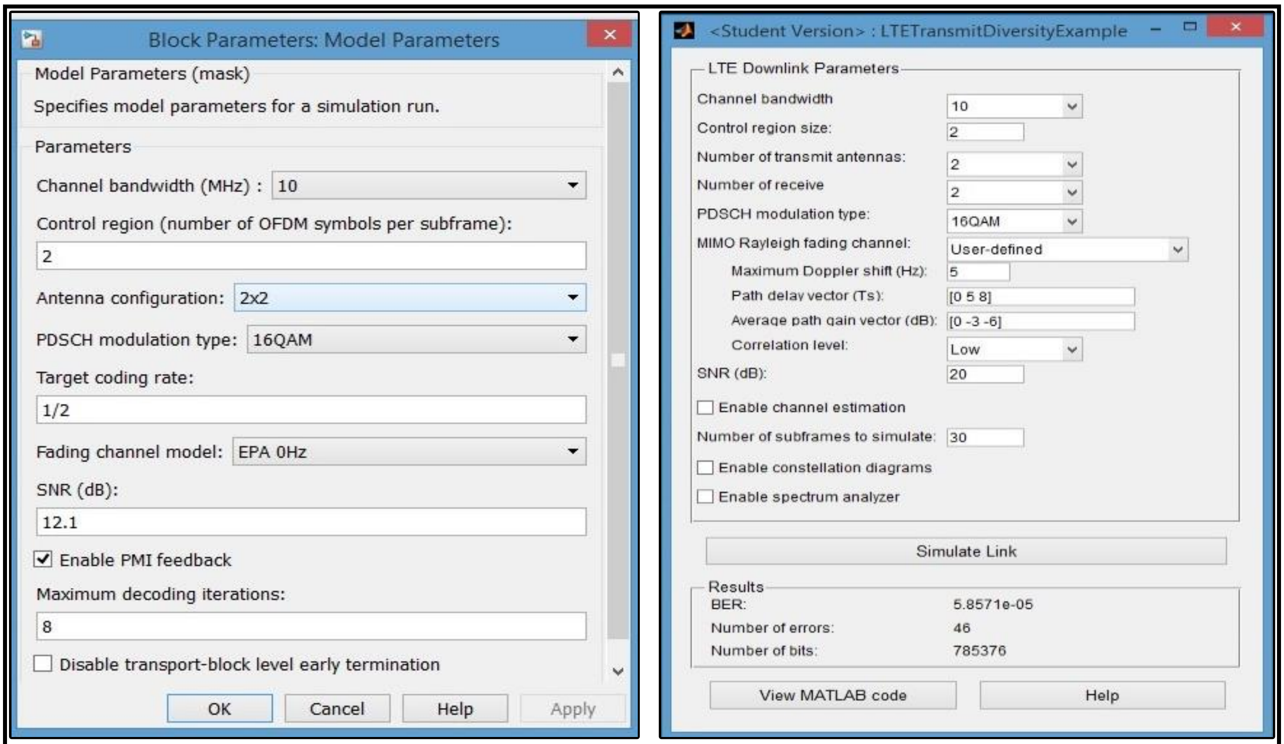
The transmission medium (surrounding environment) plays a great role in the signal propagation and to get statistical independent channels we must have to have a rich fading environment (reflection, refraction…etc.). So that each path is statistically independent, and the receiver can distinguish the data from different channel paths. Increasing the number of antennas not necessarily improve the capacity of the wireless system, as by increasing the capacity we may increase the likelihood that we get correlated channels at the receiver. MIMO spatial multiplexing increase the data rate on the expenses of Reliability (Angel Lozano, Nihar Jindal, 2010). So there is a limitation of increasing the number of antenna for achieving higher data rates. Adding to that the wireless environment undergoes random changes, so to overcome this issue we need to implements detectors at the receiver to determine the maximum likelihood between different channels (paths). So we can calibrate the system for the optimum number of antennas at the receivers and the same time maintaining the targeted system capacity. Such detectors are called maximum likelihood detectors (Wong, 2012). Adding such detectors to the system will increase the complexity of the receiver circuit, but this is the expenses that we should pay to get high data rates. Otherwise, the transmission signal will be corrupted, and the system throughput gradually decline.

2.3.2 MIMO Spatial Diversity.

From (ITU-R, 1997) definition, the purpose of spatial diversity is not to achieve greater system capacity as in spatial multiplexing. However, to make higher or better signal quality provided by the diversity gain this approach of MIMO diversity is suitable for such environment that we cannot achieve higher capacity. However, if we want more capacity, then we must know which kind of spatial diversity array configuration give us maximum capacity (A.B.Gershman, N.D.Sidiropoulos, 2005).(Refer to Chapter 4,Section 4.3.4).Spatial diversity techniques such as selection diversity, equal gain combining, and maximum ratio complaining have been introduced long time ago. All had the same goal is to achieve better signal quality or in some cases to make better coding gains. Transmit diversity had become popular recently as it became used not only on the receiver side but also on the transmitter side. Transmit diversity used either for diversity gain or combining diversity gain and coding gain. In the next chapter, we will discuss the implementation of spatial multiplexing and spatial diversity components in details with the aim of MATLAB.

Chapter Three (Design and Specification)

3.1 Model GUI Interface



Spatial Multiplexing Model Parameters *Spatial Diversity Model Parameters*

Figure 11: Simulation Model Input parameters

Figure (11) shows the model input parameters for both spatial multiplexing and spatial diversity. Before starting with the design implementation, there are a group of input parameters for both model need more attention from us. These parameters are crucial and have a direct impact on the performance of both MIMO model. The parameters are:

1. Control Region (Implemented on both model).
2. Coding Rate and Maximum Decoding Rate (only for MIMO spatial Multiplexing).
3. Correlation level.(only spatial Diversity)

However, to understand these parameters functionality impact on both MIMO model, we need to know their fundamental operation. For that reason, I give some background information about these parameters principles and why we are using it in our models. Although it looks inconvenience to have all these background information on this chapter, but the nature of the model and the research itself forces me to discuss these parameters with the design specification. However, in the end these parameters are the primary specification of MIMO model.

3.2 Spatial Multiplexing MIMO channel Design.

For designing spatial multiplexing MIMO channel, we will use the built in MATLAB Simulink provided by MATHWORKS. The model presented shows the Downlink Shared Channel (eNodeB to UE) processing of the Long Term Evolution (LTE) physical layer (PHY) specifications. Developed by the Third Generation Partnership Project (3GPP) Release 10. We will use this model to show the performance of spatial MIMO channel with different SNR. Showing how SNR impacting the performance of MIMO channel regarding the BER and the signal propagation through the Spatial MIMO channel. On the next Chapter (Test and Results) we will show a comparison between the Spatial MIMO channel and Transmit Diversity MIMO channel, but before that we must understand how these models was implemented and how we can use it to obtain the results.

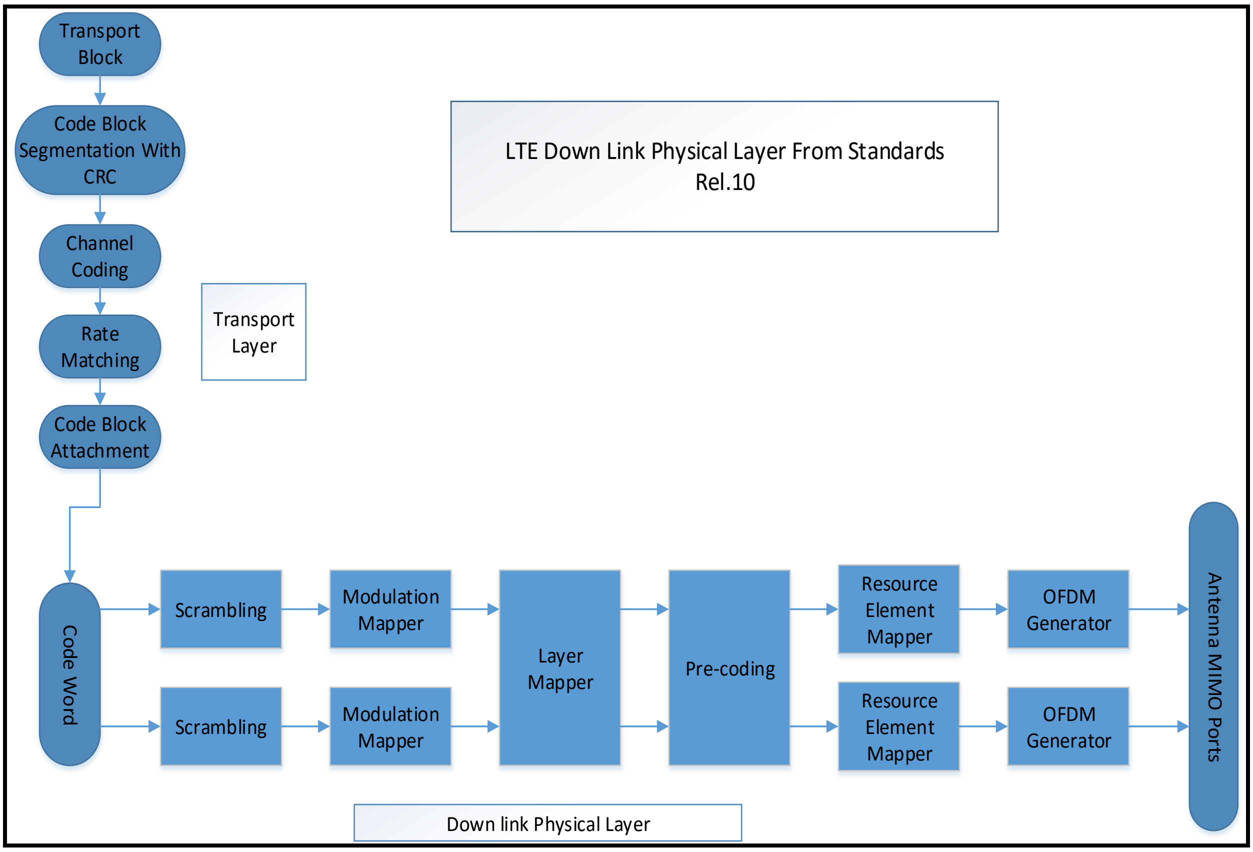


Figure 12: LTE Physical Layer from Standards (Zarrinkoub, 2012)

Figure (12) shows the standard LTE physical downlink channel, MATLAB Simulink interpret the international standards into a model that we can use to investigate the performance of LTE downlink channel. The model translates LTE standards into three principal parts:

- Turbo Channel Coding.
- OFDMA Transmission Generator.
- MIMO Channel.

3.2.1 Turbo Channel Coding.

According to (S.D.Ma, T.I.Yuk). Turbo coding is based on convolutional encoding. Where parallel convolutional encoders are concatenated to produce the coded output. Convolutional encoder in general is deferred from other types of encoding schemes by encoding the whole data stream; this will provide an error control over the transmitted date. Convolutional codes are specified by three parameters *n*, *k*, *K*. where:

k is the input data; n is the output (from the encoder), *K* is the constraint length of the convolutional encoder (convolutional encoder had *K-1* memory elements).The performance of the convolutional encoder depends on two factors, the code rate which is equal to (*k/n*) and the constraint length *K*, for longer constraint length we can achieve higher coding rate but on the expenses of delay and more complex decoder needed at the receiver.

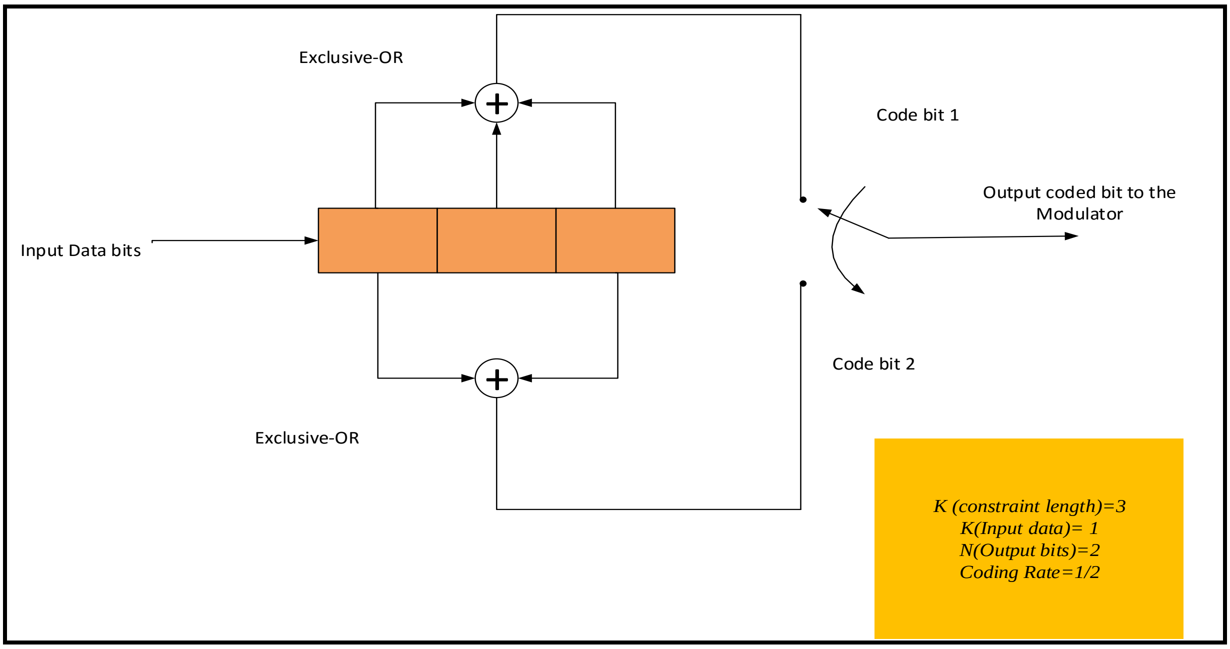


Figure 13: Basic Convolutional Encoder (S.D.Ma, T.I.Yuk)

Turbo encoding is the error correction and controlling adopted by LTE standards, which is defer from the convolutional encoding scheme that had been used by the 2G and 3G technology, although Turbo coding is based on convolutional coding but as regards its performance it considered a very high error correction functionality performances in which it is approaching the highest channel capacity boundary known as Shannon channel capacity (France Patent No. 9105279 (France), 92460011.7(Europe), 1993), the general equation for additive white Gaussian noise is given below:

$$C = B \ \log_2(1 + SNR) \text{ …….. (3.1)}$$

Where C is the channel Capacity, B is the channel bandwidth and SNR is the signal to noise ratio, whoever this equation is modified according to the propagation channel impairments, especially when we had small-scale fading channels impairments where in this case we must Sum all the channel capacity of the sub-channels which is called (water-filling).Turbo coding is based on two convolutional encoders in parallel, and the performance of Turbo coding relies on iteration for each iteration the performance of encoding being better and better, and for this turbo coding is one of the major components of LTE standards.

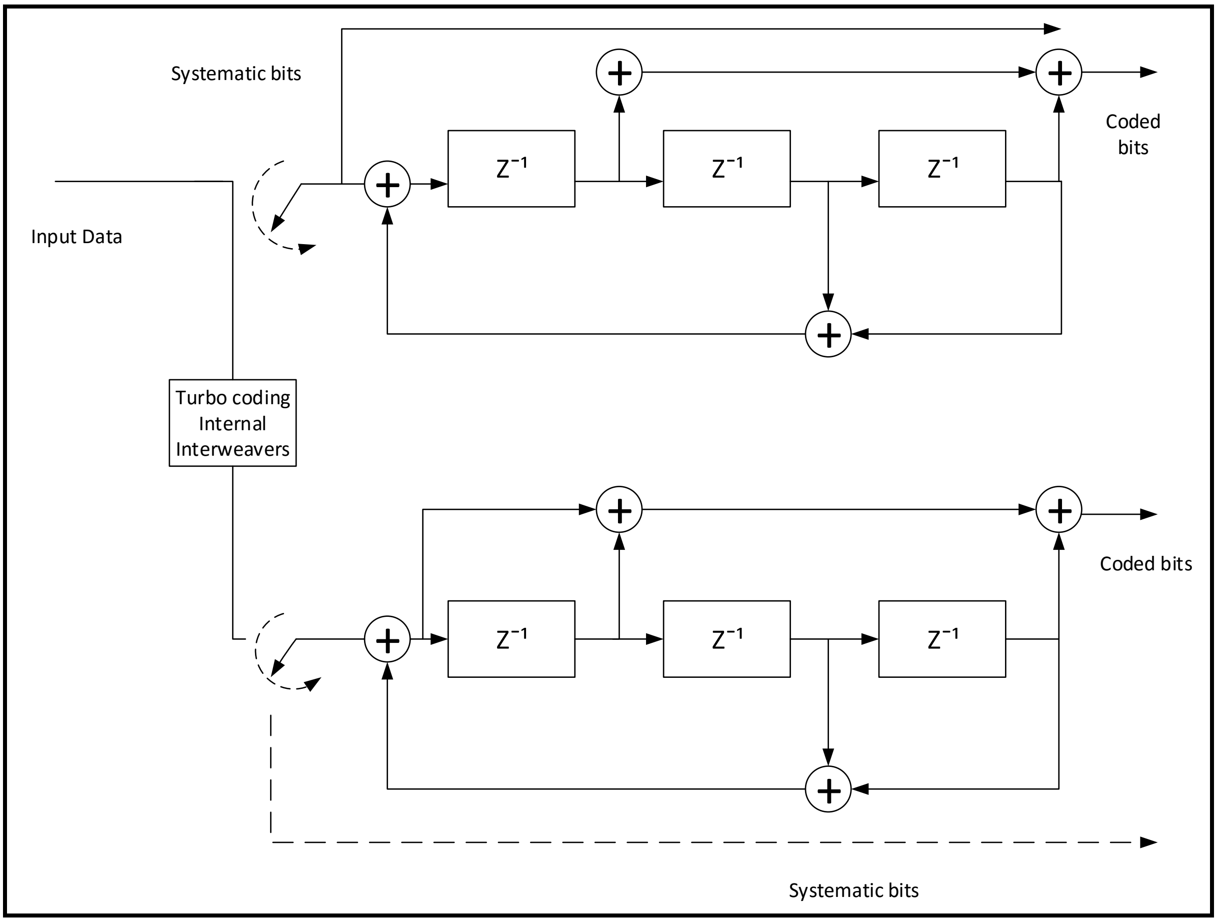


Figure 14: Turbo Encoder Scheme (Mathworks, 2013)

Figure (14) shows a Turbo encoder based on two parallel convolutional encoder with systematic output bits (systematic output means that the input bit stream also inserted in the output coded bits). The coded bits then form the code word that is feed it to the modulator. Hence, to send out through the channel. Upon received the modulated signal at the receiver, the demodulator translated the received signal to bits and fed it to the decoder. Usually a Viterbi decoder. This process is called Hard Decision where the demodulator converts the received signal to bits then sends it to the Viterbi decoder. This scheme is used till now for 2G systems, however for 3G systems and beyond 4G and especially LTE advanced systems, the demodulator at the receiver will not translate the message to bits. Rather than that it will give the probability of the received signal .and this probability quantity will be fed to the decoder, and this is called *Soft Decision* (S. Benedetto,D. Divsalar, G. Montorsi, F. Pollarab, 1996). Which highly improved the performance of decoders, hence improve the error correction and control schemes, in our simulation we will use Turbo coding for generating our codewords, and Viterbi decoder based on soft decision for decoding the code words.

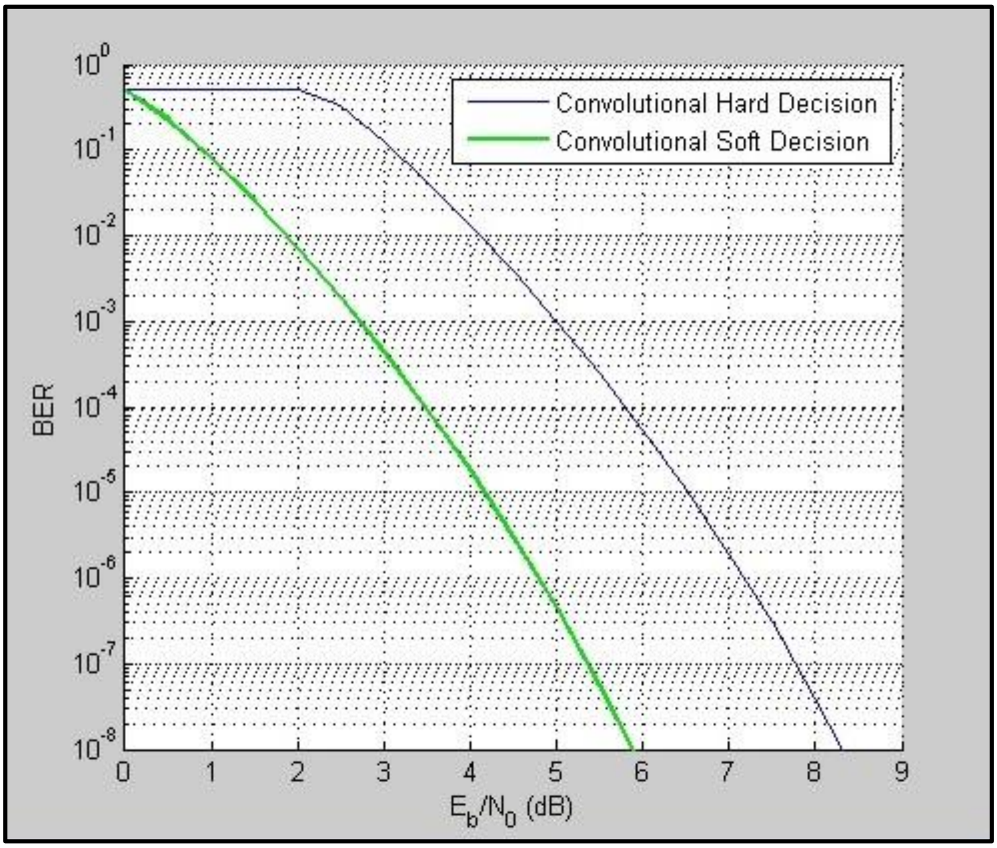


Figure 15: Hard and Soft Decision Decoding

To appreciate *Soft Decision* in improving the performances of the communication system Figure (15) shows the Bit Error Rate for two curves implemented by using BER Tool provided in MATLAB. The blue curve shows the performance of *Hard Decision.* While the green one is *Soft Decision.* And we can understand from the BER associated with the curves, that the soft decision error correction can produce much lower BER with lower E_b/N_0 (dB) than that of hard decision. Adding to that Turbo Coding uses two parallel concatenating convolutional encoders which improve the performance of error correction by running the encoding in iterations, all these new schemes participated to achieve higher data rate that the standards recommended especially for LTE systems. In our simulation, the output of the encoders will be fed to multilayer mapper to produce the codeword that represent the PDSCH of LTE system. One disadvantages of these new systems are adding complexity to the system this complexity is based on sophisticated mathematical algorithms which tend to increase the cost of the system.

3.2.2 OFDMA (Orthogonal Frequency Division Multiplexing Access).

As discussed in (Section 2.2). OFDM had been chosen as an access method for radio air interface in 3G (for example WiMax) and 4G networks (LTE). OFDM had robustness against small-scale fading especially multipath fading. Here we will illustrate how OFDMA as an access method used in LTE system and how it is implemented inside our simulation for LTE downlink shared channel. Figure (16) shows a typical multipath fading in an LTE system, where the UE received multi-copy of the transmitted signal, these signals arrived at the UE with different gains and delays associated with the propagation channel characteristic denoted as {h, d}, where (h) is the channel gain and (d) is the delay, so at the UE (receiver) we had a combination of these received signals from different multipath channels, hence the received signal at the UE according to (Zarrinkoub, 2012) can be expressed as:

$y(n) = \sum_{n=0}^{N} h_n(X_n - d_n)$ ………. (3.2)

Equation (3.2) actually representing convolution in time domain and according to (B.P.Lathi, 2005) convolution in time domain means multiplication in frequency domain. Hence:

$Y(W) = H(W)X(W)$ ……………… (3.3)

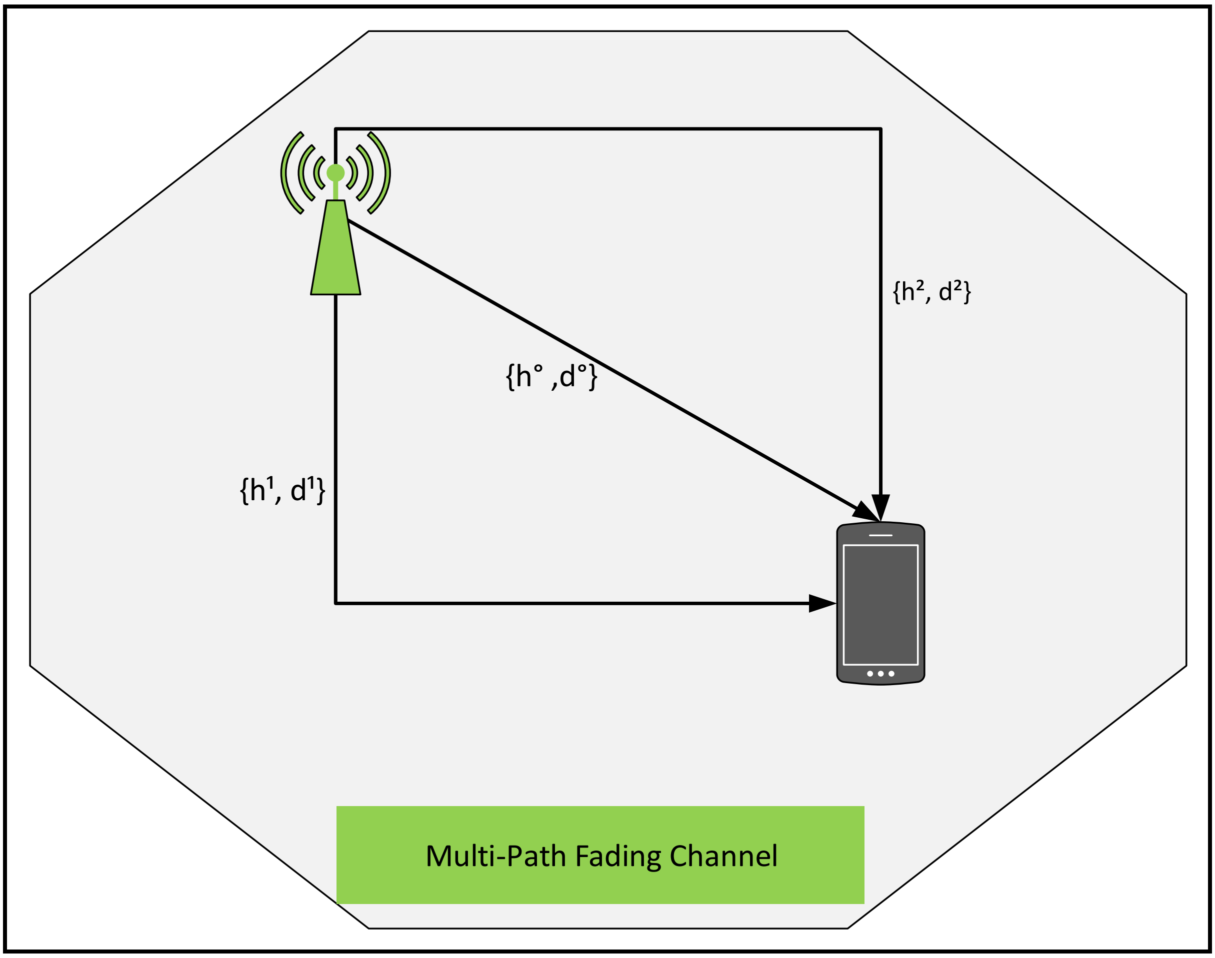


Figure 16: LTE Multi-Path Fading Channels (Zarrinkoub, 2012)

Equation (3.2) help us to understand the impulse response and frequency response of the multipath channels, where *H (W)* is the channel impulse response, and *X (W)* is the channel frequency response. And this will give us a clear understanding about the channel profile. If we could sample the frequency domain of each of these channels and find the gain of these channels then multiply it by its inverse then we can retrieve the original signal. The mentioned process is called frequency domain equalization. Recall Figure (10) and (11) in Section 2.2 for OFDM equalizer. The task here is to find or to estimate the channel response for each of these frequencies (subcarriers), and the channel estimation can be achieved through the Pilot signal. Recall that in Section 2.2 we mentioned the *Cyclic Prefix* in OFDM, cyclic prefix used by LTE OFDM system to overcome the multipath effect of the channel and another function for cyclic prefixes is used as a guard band between OFDM symbols (subcarriers).

In our simulation model, we used the above-mentioned information for building up the OFDMA signal generator, and we used channel estimation through the pilot signal to adjust the MIMO configuration under different multipath channels. From (3GPP,Rel.10, 2013) standards, the LTE frame structure gave us an insight understanding about how OFDM is working in conjunction with spatial MIMO channel to increase the data rate under certain conditions of the wireless channel propagation. For our simulation model, the model adopted (LTE type 1) frame structure which is based on frequency division duplexing (FDD).

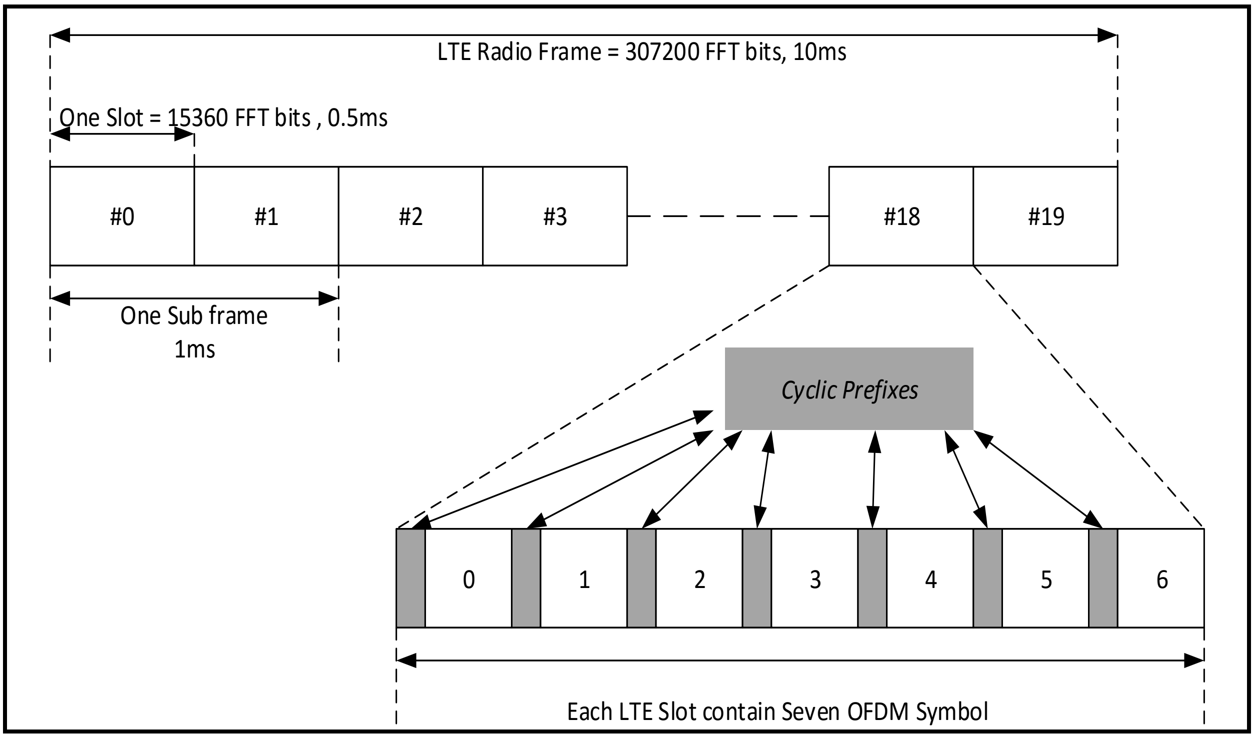


Figure 17: LTE Frame Structure (3GPP,Rel.10, 2013) (Frame Structure - Downlink , n.d.)

Figure (17) shows LTE Radio frame structure which is comprised of ten subframes each with 1msec. duration the entire frame then is 10msec. for the total LTE radio frame, each subframes are divided in to two Slots each with 0.5msec duration and each of these slots consisted from Seven OFDM symbols, separated by the cyclic prefixes. From Figure (17), the first cyclic prefix (CP) in the slot is 5.2µsec with 160 FFT bits (samples), the remaining CPs are 4.7µsec with 144 FFT bits (samples), and for the OFDM symbols are 66.7µsec with 2048 FFT bits (samples), which represent the useful data. This information is mandatory to understand for our simulation model and what inside the model are happening; these structures will form the LTE-PDSCH that will be sent through the MIMO channel. (Leo Montreuil, Rich Prodan, Tom Kolze, 2013).

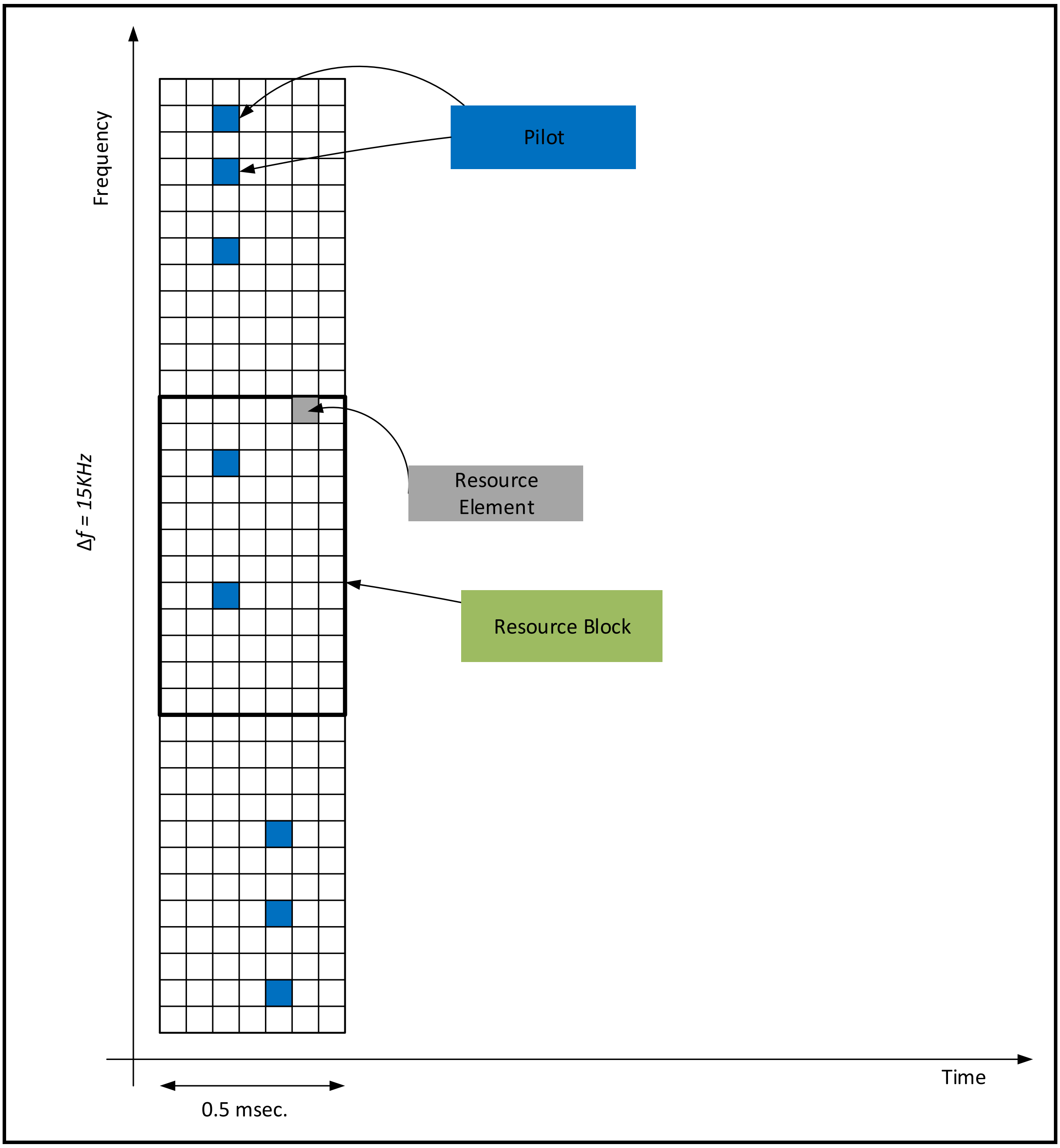


Figure 18: LTE implemented OFDM (3GPP,Rel.10, 2013)

Figure (18) shows what will be transmitted over the MIMO spatial multiplexing channel. In LTE the OFDM is implemented as *Resource Blocks* (Erik Dahlman, Stefan Parkvall, Johan Sköld, 2014). Each of these resource blocks is constructed by seven resource elements and twelve OFDM subcarriers, the OFDM subcarriers are divided in time domain into seven resource elements as we mentioned earlier. The resource blocks had bandwidth of 180 KHz, (12 x 15 KHz (subcarrier spacing)) this number is differ according to the available channel bandwidth for LTE transmission.

The number of resources blocks according to (3GPP,Rel.10, 2013). Depends on the possible number of OFDM subcarriers, and the number of subcarriers depends on the available transmission bandwidth, In our simulation we will simulate the LTE PDSCH within different bandwidth so it is necessary to know the number of transmitted resource blocks associated with each transmission bandwidth.

Channel B.W (MHz)	1.4	3	5	15	20
Transmission B.W Configuration (N_{RB})	6	15	25	75	100

Table 2: LTE B.W versus Resource Block Number (3GPP,Rel.10, 2013)

3.2.3 Spatial Multiplexing MIMO.

In (Section 2.3.1). We discussed MIMO spatial multiplexing in brief, however in this section we will discuss it in more details and how the MATLAB Simulink model provided can be used to check the performances of MIMO spatial multiplexing. As we previously mentioned the aim of spatial multiplexing is to increase the data rate, and that can be achieved with high error correction algorithm (Turbo Coding), and robustness access method which is OFDM. The MIMO spatial multiplexing is based on linear algebra and especially Matrix algebra, but what shall we put inside our matrix? When we talk about multipath fading and that the receiver received multi-copy of the transmitted signal from different paths with different gain and delay (Figure 16). These parameters will be the main elements of our matrix. And because of that we used multiple antennae for the transmitter side and multiple antennae for the received side (MIMO Antenna) then we can correspond each received message to its originated antenna (transmitter) and its received antenna (receiver). Equation (3.3) will be the key factor to retrieve the data signals at the receiver by distinguishing different data streams that had been sent over different antenna, recall that for MIMO spatial multiplexing we are increasing the data rate by transmitting different data stream over different antenna and it is the receiver task to distinguish between different data streams that been collected from different multipath.

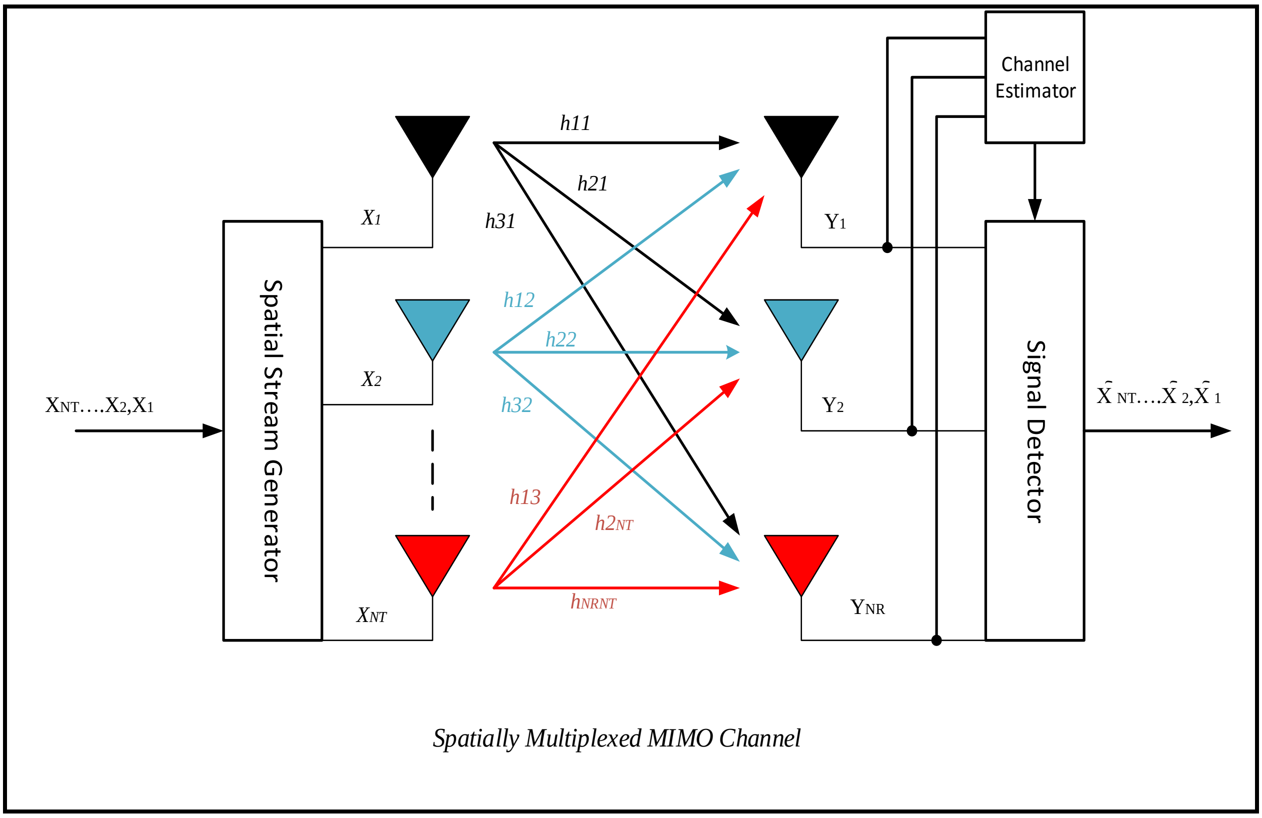


Figure 19: LTE Spatial Multiplexing (Cho, et al, 2010)

Figure (19) shows a theoretical MIMO channel consisted of ($N_R \times N_T$) received and transmit antenna. As figure (19) showed, each receiver antenna received a copy of the signal from different transmit antenna, these copies can be represented by a $[N_R \times N_T]$ matrix. As we mentioned earlier, each element of this matrix will represent the multipath channel of the transmitted signal. We can say that the produced matrix from the antenna configuration is representing our MIMO spatial multiplexing wireless channel. Figure (19) also shows an important element and very essential element for the performance of the MIMO channel in spatial multiplexing configuration and this element is the *Channel Estimator*. The main functionality is to readjust the antenna configuration depending on the state of the received pilot signal from the transmitter. However, the pilot signal are sent on periodically intervals so that both the receiver and the transmitter are aware of the channel condition. As we mentioned in Section (3.1.2) these pilot signals are carried by the OFDM signals, or we may say inside the resource blocks. With help of Figure (19) we can rewrite Equation (3.3) as a matrix equation, keeping in mind that the signal at each receiver antenna is the sum of these multi copies of the signal from the other transmitted antennas in the MIMO.

According to (Cho, et al, 2010), the new modified equation (3.3) will be as follow:

$$\begin{Bmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_{Nr} \end{Bmatrix} = \begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1Nt} \\ \vdots & & \dots & \vdots \\ h_{1Nt} & h_{2Nt} & \cdots & h_{NrNt} \end{bmatrix} \begin{Bmatrix} X_1 \\ X_2 \\ \vdots \\ X_{Nt} \end{Bmatrix} + [n] \text{ ………….. (3.4)}$$

Equation (3.4) is the mathematical representation of MIMO spatial multiplexing channel for (Y_{Nr}) received signal from multiple received antenna. Where (X_{Nt}) is the independent transmit data stream from multiple transmit antenna, while the matrix (h_{NrNt}) represent the channel impulse response of the MIMO spatial multiplexing channel and finally $[n]$ representing the AWGN as a vector. Equation (3.4) can be solved if and only if the matrix (h_{NrNt}) is inversable, and the trick here is how to insure that all the elements of the matrix (h_{NrNt}) are not similar? Recall from section (2.1.2) that small-scale fading follows a probability distribution function (PDF), and it is obvious that we may get two rows of the matrix (h_{NrNt}) with the same entities. And under this situation the Eigenvalue of the matrix will equal to zero, and this is mean that Equation (3.4) have no solution. The only way to overcome this problem, actually comes from Matrix algebra again by using Singular Value Decomposition (SVD) which we can factorize the matrix (h_{NrNt}) to insure that we have a solution for Equation (3.4). This can be done with the help of the channel estimator through the pilot signal that had been transmitted from MIMO transmit antennas then calculate the SVD for the matrix(h_{NrNt}). If no solution obtained, then the receiver will send back a signal to the transmitter to readjust the antenna setting. for example, reduce the configuration from (4×4) to (2×2) to guarantee a solution for the Equation (3.4), this feedback signal from the UE is called the *Rank Index* (RI) which identifies how many layers the UE can distinguish. All these mathematical algorithms add an immense complexity to the system but this is the cost that we must pay for high data rates. Now after we cover all the major parts of the MIMO spatial multiplexing channel that have been provided from the standards. We will now look at the environment that all these components are assembled in the Simulink model. Also, we will show which kind of parameters that we will use to investigate the MIMO spatial multiplexing performance.

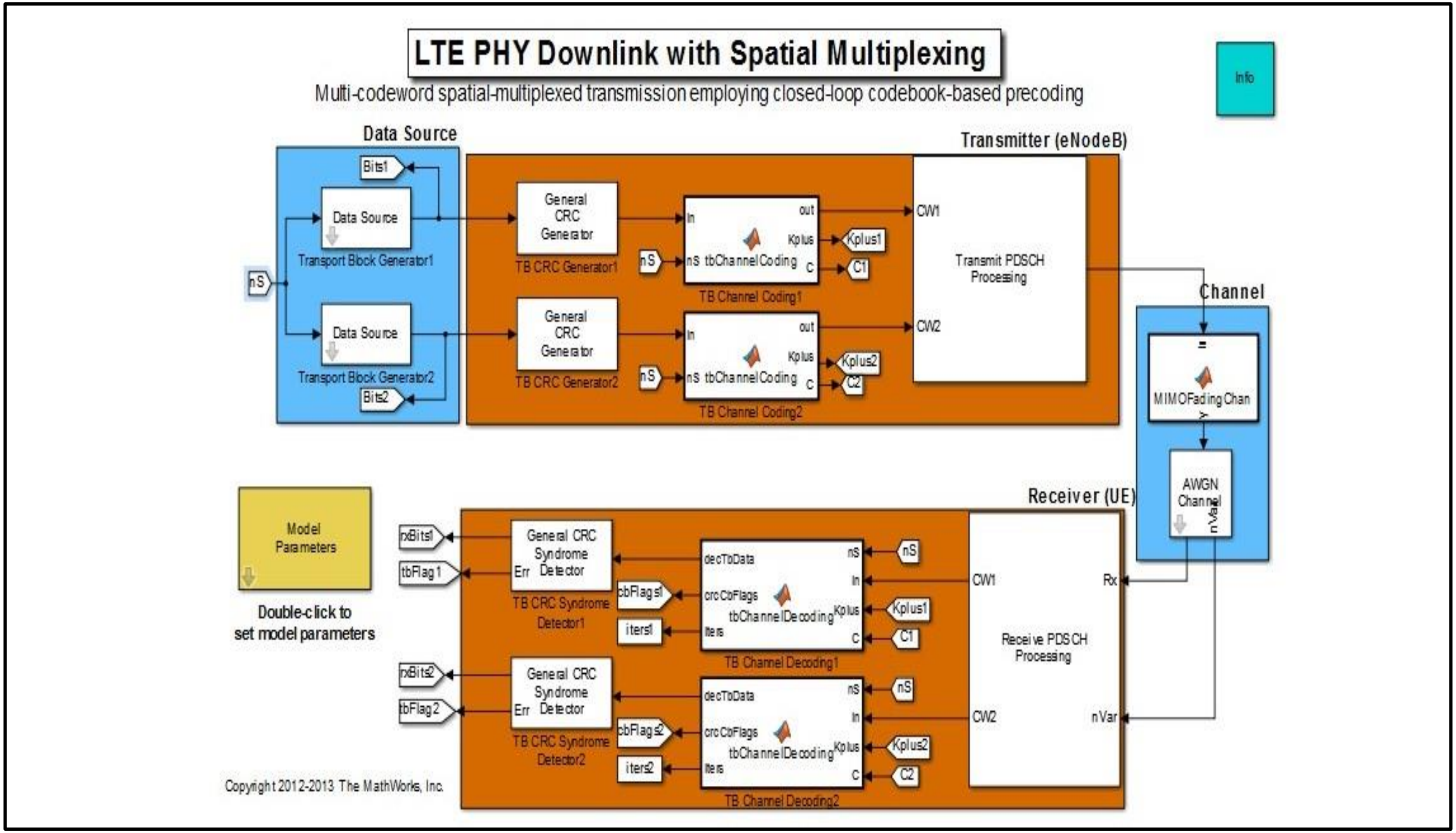


Figure 20: LTE MIMO Spatial Multiplexing (Zarrinkoub, 2012) (Mathworks D. , 2014)

According to (Mathworks, 2013) and from Figure (2). The model for LTE spatial multiplexing, is consisted from four major parts and these parts are illustrated in Table (3) below:

Block	Description and functionality
Data Source	Responsible for generating the payload data per each LTE sub-frames, where it received the data from the signal generator that is generate cell-specific signal according to 3GPP Rel.10. Referring to section 3.1.2 for LTE frame structure, here the model adopted 2 OFDM symbols/2 slots/sub-frame/antenna port.
Transmitter	The transmitter block represents the eNB, which have three principal parts. 1. The cyclic redundancy check bits generator which is a Simulink block that we can set the polynomial generator and the checksum per frame. 2. The Turbo channel encoder implemented by (MATLAB function script). 3. The transmit processing of the PDSCH block which is contain the scrambler, Modulators (adaptive modulation), layer mapper (this is for the generation of codewords that is send to the spatial multiplexing). Also, spatial multiplexing precoder where the PDSCH is pre-coded for spatial multiplexing, remapper where it is responsible for generating the resource blocks. (Refer to Section 3.2.2, Figure (18), finally the OFDM signal generator where the Resource Blocks are carried out by the OFDM subcarriers to the channel through the antennas.
Channel	The channel has two parts, the MIMO fading channel that is implemented by using MATLAB function, and AWGN which is a block provided by the communication tool box.
Receiver	The receiver represents the UE, and it is consisted of, the descrambler, demodulation, layer de-mapper, and the OFDM demodulator. The major differences with the transmitter side is two components, which are the decoding scheme (Hard or Soft) decision refer to Section (3.2.1), Figure (15). And the other component is the channel estimator, refer to Figure (19), these two component build by MATLAB script.

Table 3: MIMO Model Description

Figure (21) and (22) shows the implementation of the PDSCH transmit processing and PDSCH receive processing respectively, note that these two block are parts from the transmit block and the receiver blocks respectively.

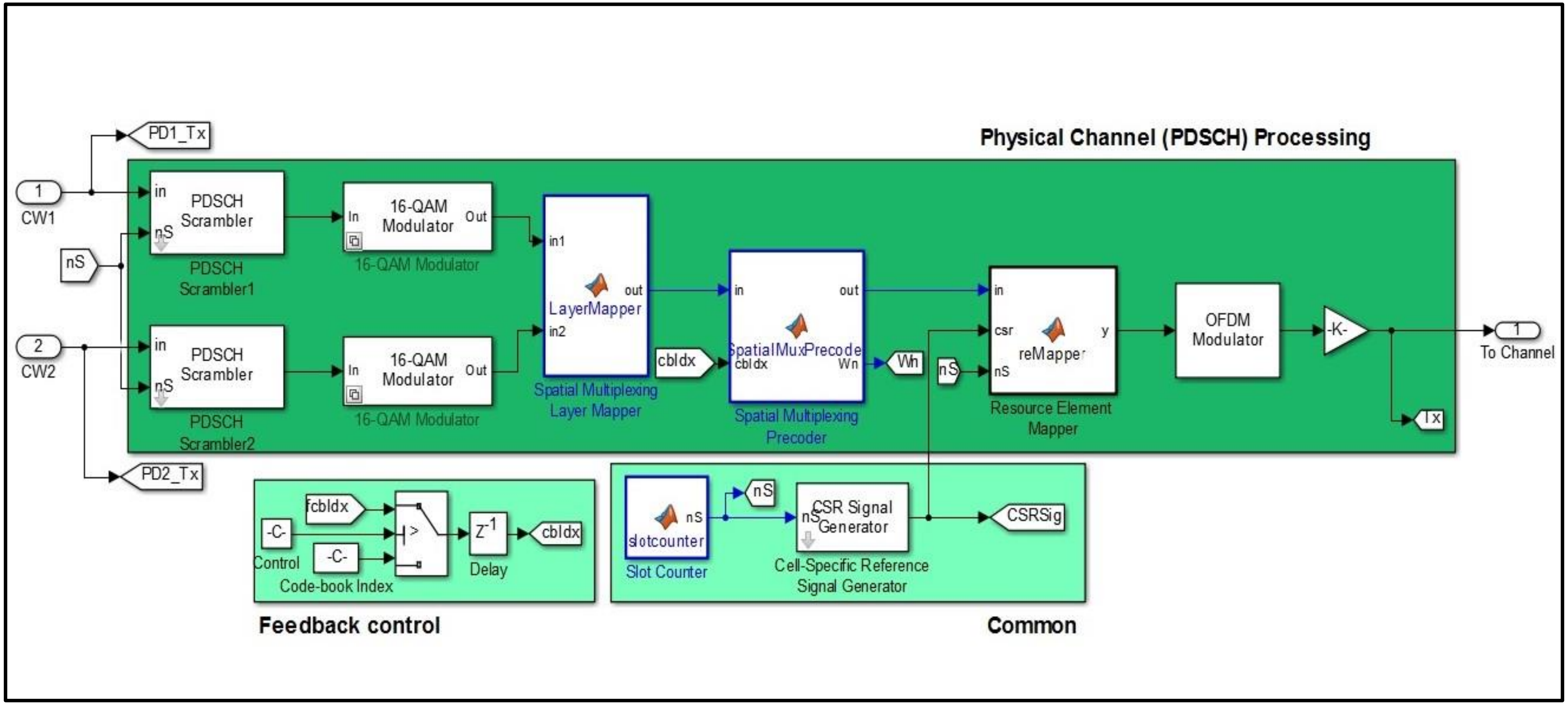


Figure 21: PDSCH Transmit Processing (Zarrinkoub, 2012) (Mathworks D. , 2014)

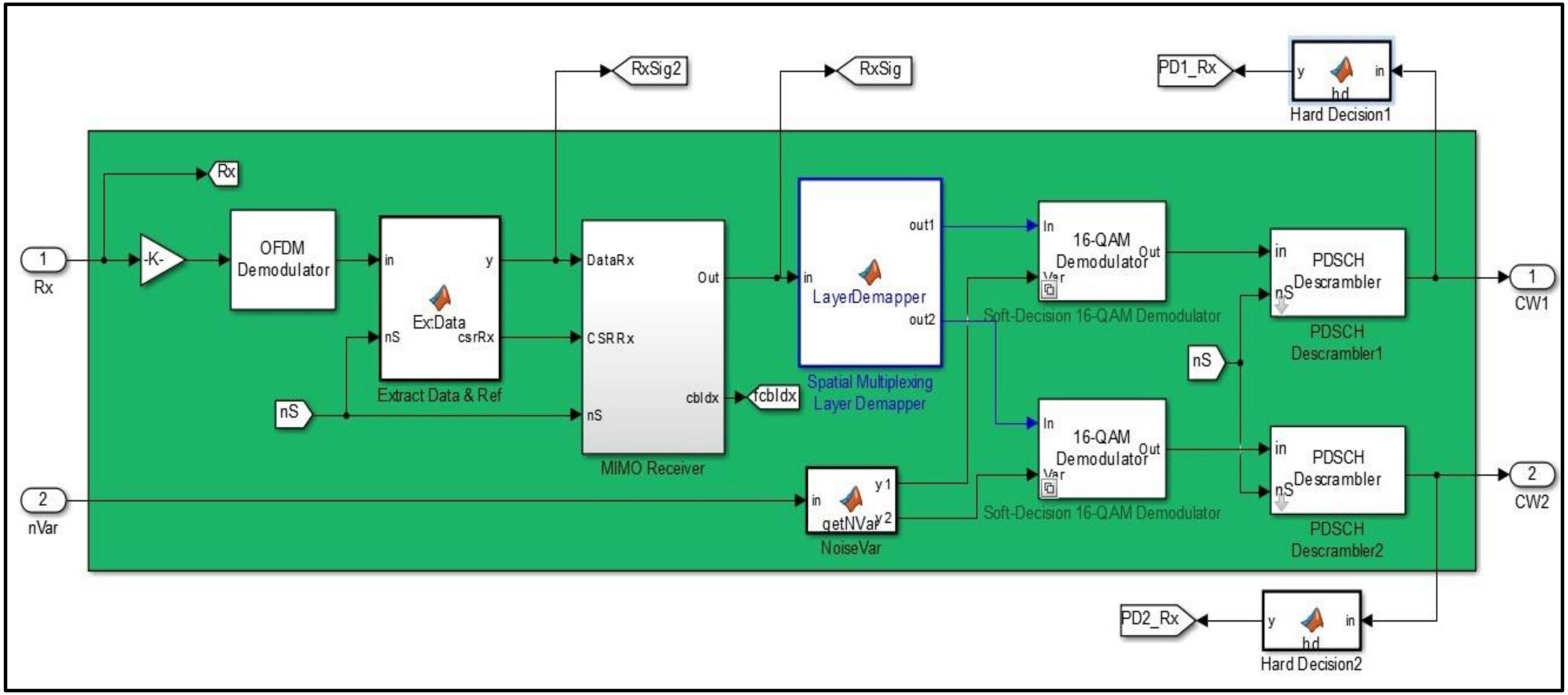


Figure 22: PDSCH Receive Processing (Zarrinkoub, 2012) (Mathworks D. , 2014)

3.3 MIMO Spatial Diversity

In Section (2.3.2) we discussed spatial diversity in brief. An essential component of the spatial diversity is similar to that of spatial multiplexing. And the mythology of implementation is based on LTE 3GPP Rel.10. However, the model application is based on MATLAB GUI simulator, and we will use this model for testing and obtaining the result. Chapter 4 will be dedicated for test and results, meanwhile in this section there are some relevant specifications for MIMO spatial diversity that we must cover to have better understand the system behaviour. Also, how we can optimize our network performances by implementing both technologies (spatial multiplexing and spatial diversity) and switch's between the two technology depending on the current status of the wireless communication channel, where this process is considered as self-optimizing which is in turn considered as Self-Organizing Network.

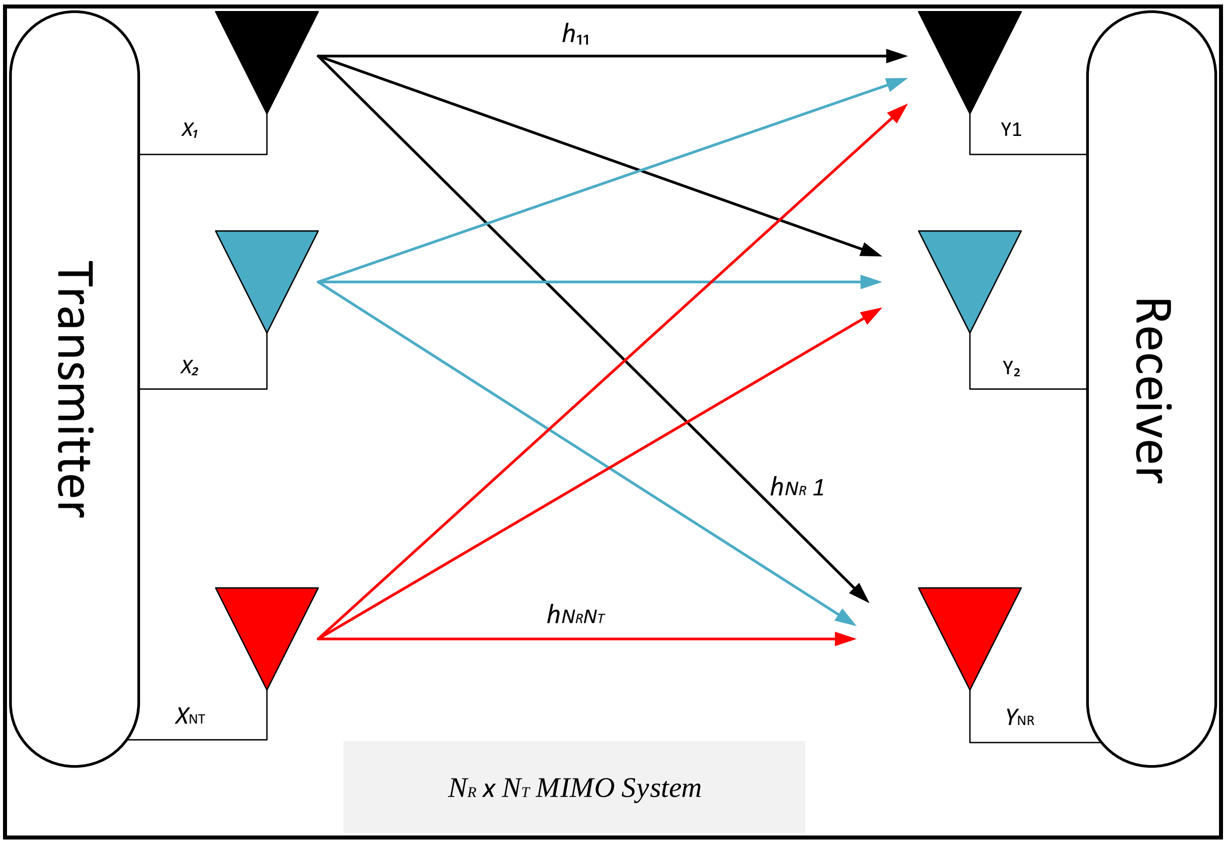


Figure 23: MIMO Spatial Diversity (Cho, et al, 2010)

Figure (23) depict an MIMO spatial diversity technique, and according to (Wong, 2012). This technology was introduced in the late of the nineties of the last century approximately near 1998. The primary advantages are to increase the channel gain hence increasing the level of the received signal at the receiver; MIMO spatial diversity can achieve better signal quality by using three techniques, *Selection Diversity, Equal Gain Combining* and *Maximal Ratio Combining*. Selection diversity based on monitoring the instantaneous SNR of each diversity branch, then the receiver continually switches to the branch (antenna) with highest instantaneous SNR and discard the other SNR from other branches. Equal gain is combining in the other hand use more practical way to get better SNR and that by exploiting the other branches SNR and combining it to get better SNR. Finally, maximal ratio combining considered as the best diversity combining method where the diversity branches are co-phased, and each branch will get a weight that representing the instantaneous SNR of that branch. So naturally the branch with better SNR get a higher weight and so on, by this we will get better performance than the other two technique. However, the idea is to reduce correlation between transmit and receive antennae (G.J. FOSCHINI, M.J. GANS, 1998). For our simulation we will adopt maximal ratio combining with the use of space block coding.

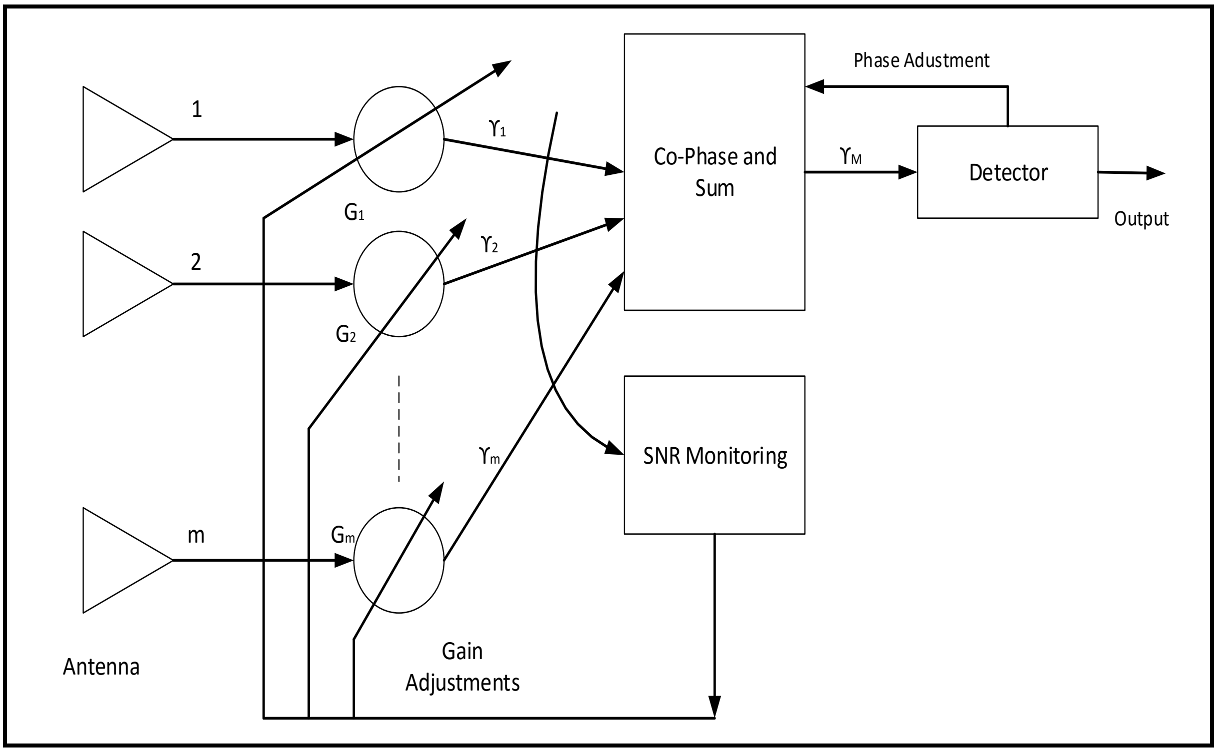


Figure 24: Maximal Ratio Diversity (Wong, 2012)

Figure (24) describe the typical operation of maximal ratio diversity combining. Where the co-phase block sums out, the average received SNR from each diversity antenna with their weights that assigned to it according to the average SNR (the higher the average SNR the greater the weight that is given to that branch). The gain controller plays a great role for adjusting the gain so that maximize the average received SNR. (Wong, 2012) claims that, if (γ_i) represent the received SNR from the i'th diversity antenna and the average received SNR denoted by (Γ) then the maximal ratio combining is equal to:

$$\Gamma_{\max ratio} = \sum_{i=1}^{N} \Gamma_i \text{ ….. (3.5)}$$

Equation (3.5) shows that the average output (maximal ratio) SNR is the sum of the input SNR as an average over time from each diversity antenna, assuming that the diversity antennas are independent, identically distribute. The model used to simulate MIMO spatial diversity, in some parts are similar to that of spatial multiplexing. But the main differences are the coding type that is been used. Where in spatial multiplexing, we used turbo coding, and this is obvious for such a scheme as the aim is increasing the data rate. While the coding system adopted in spatial diversity is space-frequency block coding (SFBC) as a combining method to achieve diversity gain (Claude Oestges, Brun Clerckx, 2007). Where coding is applied in the frequency domain (OFDM) carriers rather than the time domain (OFDM Symbols), Figure (17) in Section (3.2.2) gave an understanding about the OFDM symbols. Table (4) lists out the main parts of the model implementation and in fact it is not much defer from Table (3) entities but with different functionality.

Function	Description
Data Source	Where it consisted of Physical Channel (PDSCH) Processing, Scrambling where the encoded bits are bit-level scrambled for time synchronization and reducing the inter-carrier interferences. Also, Data Modulation, Layer Mapping and Precoding, where the received transport blocks are converted to codewords by the physical layer and assigning it to antenna ports. Also, Resource Element Mapping where the pre-coded are grouped for each antenna, Cell-Specific Reference Signals used for channel estimation at the receiver, (CSR) configured for one, two and four in a cell, and this prevent interference from another antenna transmission.
Transmitter	OFDM Transmission.
Channel	MIMO Rayleigh fading channel over multiple links.
Receiver	The receiver represent the UE and it is consisted of: ***OFDM receiver***, ***Channel Estimation***, ***Transmit Diversity Combining, demodulator and descrambler.***

Table 4; MIMO Spatial Diversity Components

3.4 Generating LTE PDSCH (Physical Downlink Shared Channel)

For both technology systems MIMO spatial multiplexing and MIMO spatial diversity the simulation model adopted the LTE PDSCH packets channel to be sent over the MIMO channel. However, the reason is that all of the data and control messages from the upper layers of LTE radio layers are terminated in the physical layer (refer to Figure (3) and (4) in Section 1.3). We discussed in Section (3.2.3) and (3.3) a specification for both technology systems and the component associated with the plans in details. We can notice that there are some components that are used by both schemes, and that is because of the PDSCH packet implementation, so it is mandatory to understand how these packets are generated and how they are been sends over the MIMO channel. Referring to Figure (3) and (4) in Section 1.3, and according to (3GPP,Rel.10, 2013) standards the physical layer converts the transport block received from the MAC layer into a codeword. And there are a several steps involved depending on the received transport block length; these steps are including the following:

1. Adding 24 bit CRC (cyclic redundancy check), to insure that the transmission was successful or not by using hybrid ARQ to send ACK or NACK back to the sender (refer to Section 3.1 for more details on the physical layer functionality).
2. Segmentation of the received transport block into code blocks, according to the standards the code blocks length must be between 40-6144 bits.
3. Process the code blocks with turbo coding (refer to Section 3.1.1 Turbo coding) with different coding rates.
4. Reassemble the code blocks into a single codeword.

All the above points had been implemented in our models for both spatial multiplexing model, and spatial diversity model (refer to Section (3.2.3) and (3.3) respectively). In the receiver side the receiver (UE) can be configured to receive one or two codewords in a single transmission interval. However, the physical layer job is not finished yet, where after producing the codewords the physical layer then convert the codewords into modulation symbols. (Don, 2011) Claims that the physical layer must do the following:

1. Scramble the content of each codeword, to prevent inter-carrier interferences also to provide synchronisation.
2. Convert the bit sequences into the corresponding modulation scheme (16 QAM, 64 QAM, and QPSK).

3. Assign the modulation symbols to one or more layer (refer to Figure (20) Section (3.2.3)), depending on the MIMO configuration and the number of codewords used. For MIMO spatial diversity, the modulated symbols are distributed equally among the antenna diversity layer (2) or (4) layers in a round-robin way. While the codewords in spatial multiplexing are allocated among one, two, three, or four layers depending on the feedback signal from the UE or simply the rank index (RI),(Section 3.1.3).

The final step that the physical layer do is assigning these layers into antenna ports and to that the physical layer will first do the following:

- Applying pre-coding factors to the modulation symbols for each layer.
- Map the pre-coded symbols to its antenna port.
- Assign the modulation symbols to be transmitted on each antenna port to specific resource elements (the subcarriers and symbols within the resource blocks, Figure (18) Section (3.2.2).
- Generate the time domain OFDM signal for each antenna port.

Codewords	Layers	Mapping
1	1	The codeword is mapped to a single layer.
1	2	The codeword is split between the two layers (even/odd).
2	2	Each codeword mapped to its port but we must take in our consideration that both codewords had the same length.
2	3	The first codewords is mapped to the first layer and the second is split in to (even/odd), taken in our consideration that all the codewords must have the same length, hence the first codewords must be half the length of second codewords.
2	4	By the same mean, the first codeword is split in to (even/odd) then feed to the layer, and the second one also splits in to (even/odd) then feed to the layer, both codewords must be in the same length so each layer carry the same number of symbols.

Table 5: Codewords versus Mapping Layers (Don, 2011)

Chapter Four (Testing and Results)

4.1 Test Clarification.

Before running the test and identify the input parameters to the simulation model. I would like to revise important points that had been discussed in details in the previous chapters and sections, just for better understanding of the test for both MIMO spatial multiplexing and MIMO spatial diversity.

1. The aim of the test is to show the performance of the two scheme under different propagation channel condition and how we can use them together on one system.
2. Both technology schemes are implemented according to LTE 3GPP Rel.10 standards.
3. For both technology schemes we used the LTE physical downlink shared channel (PDSCH) (Section 3.4). As a reference for implementing the data that will be transmitted and received through the MIMO channels, and that is because of all data and signalling messages are processed from upper layers and encapsulated finally in a PDSCH packet, (refer to Figure (3) LTE radio layer).
4. The results will be arranged in tables with appropriate illustration for the results.
5. Regarding Delay Performance I will consider the execution time of the model for different input parameters as a reference delay for the system.
6. The Simulink model process one LTE PDSCH sub-frame per time step.
7. Figure (19) is the model that we will run to investigate the performance of MIMO spatial multiplexing.
8. For MIMO spatial diversity we will run the MATLAB script model (LTETransmitDiversityExample.m).
9. All related scripts and MATLAB functions codes that will be used to simulate both technology schemes will be in a separate appendix.
10. The models are implemented with the help of MATLAB and Simulink tool boxes especially communication tool box, DSP toolbox and BER tool. The licences are registered and activated as a student version (R2014a). It is important to understand that these model will not run if there are no activated licenses for the MATLAB especially when we use Simulink model in conjunction with BER Tool.
11. The receiver (UE) are configured to receive two codewords (Section 3.3) for both model schemes.

4.2 Testing MIMO Spatial Multiplexing.

Before testing the MIMO spatial multiplexing we must identifies the input parameters to the model. Table (6) list the input parameters to the model with explanation for each input.

Input Parameter	Description
Channel Bandwidth (MHz)	The available channel bandwidth is (1.4, 3, 5, 10, 15, 20) MHz, where according to the channel bandwidth we determine the number of Resource Blocks (Table (2) Section (3.2.2).
Control Region	Where the number of OFDM symbols per frame is chosen, the control region must be set for this model either 1,2 or 3 OFDM symbols for number of resource blocks greater than 10 (i.e. for channel bandwidth greater than 1.4 MHz).
Antenna Configuration	Here we will chose either (2×2) antenna configuration or (4×4) Transmit antenna configuration.
PDSCH Modulation Type	We had three types of modulation schemes for PDSCH data (QPSK, 16 QAM, and 64 QAM).
Target Coding Rate	Here we may set the Turbo coding rate (1/2, 1/3, 2/3…etc.). Section (3.2.1).
Fading Channel Model	We had multiple options here; we can choose static flat fading channel, or we will take in consideration the movement of the (UE). And the result of the Doppler effect and for that we had from LTE standards we had, Extend Pedestrian A model (EPA), Extend Vehicular A model (EVA), for our model we will switch between these types of fading channels. (Refer to Section 2.1.2).
Signal To Noise Ratio	The most important parameter that we will change it over a range of different SNR to check the performance of MIMO spatial Multiplexing model.
Maximum Number of Decoding Iteration	In our test I will use different Iteration decoding in most 3 and 6, to reduce the simulation time as for higher that 6 iterations takes a very long time for execution. Section 3.2.1
***Optional (Enabling PMI Feedback)**	PMI stand for Pre-coding Matrix Indicator and it is used in conjunction with the Rank Index (RI) to optimize the resource allocation between different users. Section (3.4). We will keep it On for all our tests scenarios.

Table 6: MIMO Spatial Multiplexing Input Parameters Description

4.2.1 First Scenario Spatial Multiplexing.

In this first scenario we will investigate the performance of MIMO spatial multiplexing channel under the following input parameters:

Input Parameter	Configuration	Input Parameter	Configuration
Channel BW	20 MHz	Coding Rate	1/2
Control Region	2	Fading Channel	EPA (0HZ)
Antenna Configuration	(2×2)	SNR	20 dB
Modulation Type	16 QAM	Decoding Iteration	6

Table 7: Scenario 1 spatial Multiplexing Input Parameters

After running the model for the given parameters we get the following results:

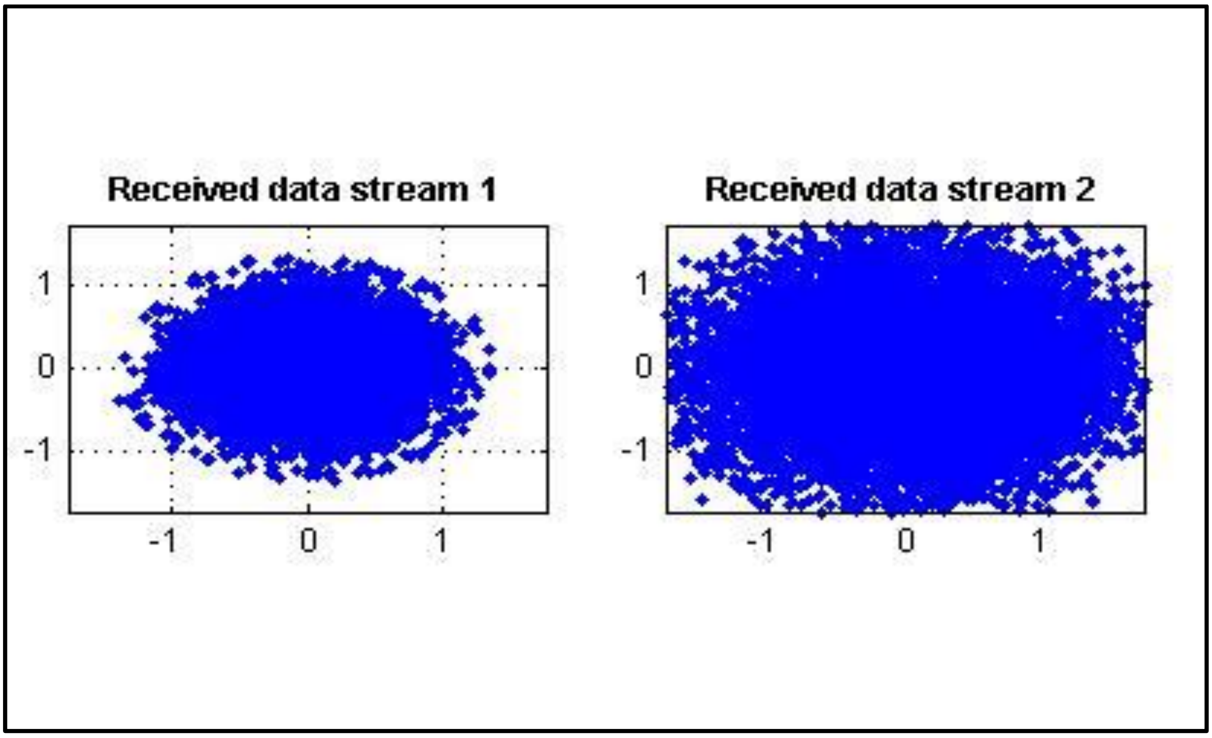


Figure 25: Scenario 1 Spatial Multiplexing Received Data Streams

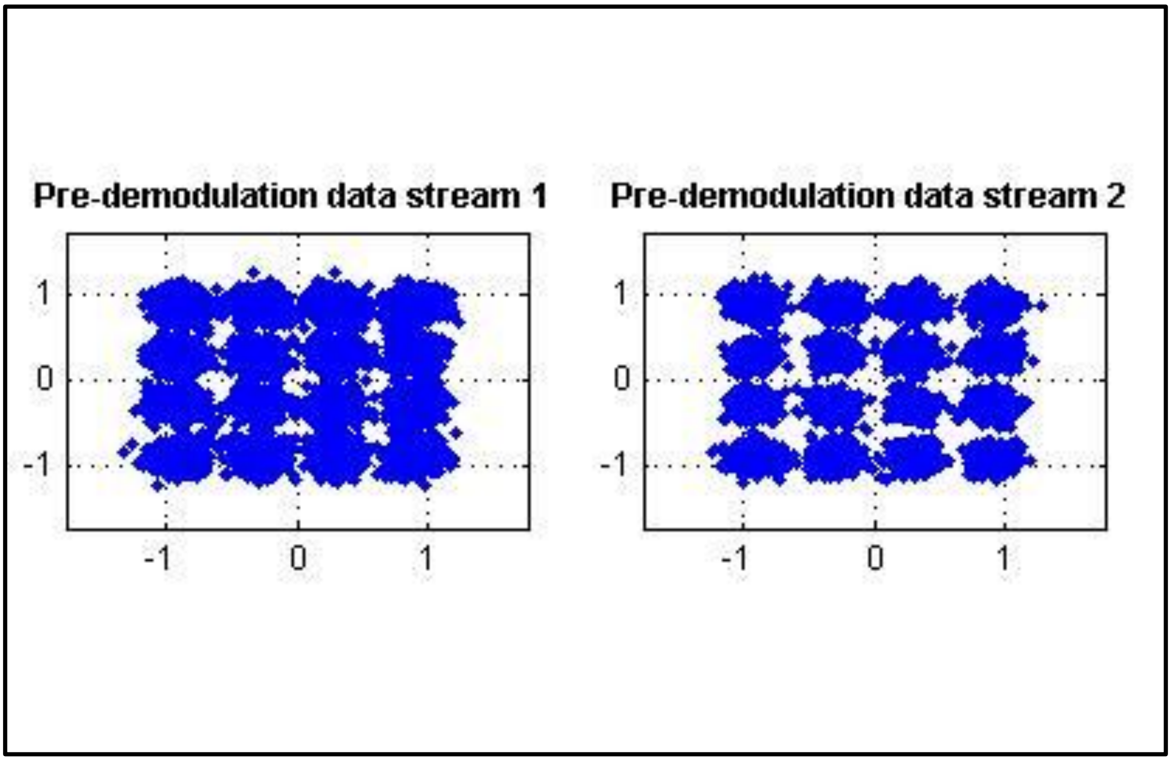


Figure 26: Scenario 1 Spatial Multiplexing Pre-demodulation

Figure (25) and (26) shows the received data stream from the (2×2) antenna ports and the same data streams before demodulation respectively. From the Figure (25) we can conclude that the first data stream are more subjected to frequency-selective fading. Hence, we had ISI due to that the signal bandwidth is larger than the channel coherent bandwidth $B_s > B_c$ and the symbol time is much less than the RMS delay spread $T_s \ll \sigma_\tau$ (section 2.1.2). Table (7) lists collected results for scenario (1):

Output Parameter	Codeword One	Codeword Two
PDSCH BER	0.001515	0.0003037
Codeword BER	0	0
Transport Block Error Rate (MAC Layer)	0	0
Maximum Data Rate Per Codeword (Mbps)	25.456	25.456

Table 8: Scenario 1 Results

Table (7), shows that the BER in the PDSCH packets are subjected to frequency selective fading, where PDSCH packets are the one who propagate through the wireless channel. But because of the powerful decoding scheme based on hard decision iterations (Section 3.2.1). Where we decided, six iterations for our scenario and each iteration the performance of error correction and control increased (we chose high SNR that may not need a lot of iterations). Hence, we received both codewords without error. The transport block (MAC layer block) was also without any error. This scenario shows that the received data rate per codeword is 25.456 Mbps and for a UE configured for two codewords per interval this is mean 50.912 Mbps per UE; this is quite right if we insure smart design for our network dimensioning (Figure1, Section 1.2).

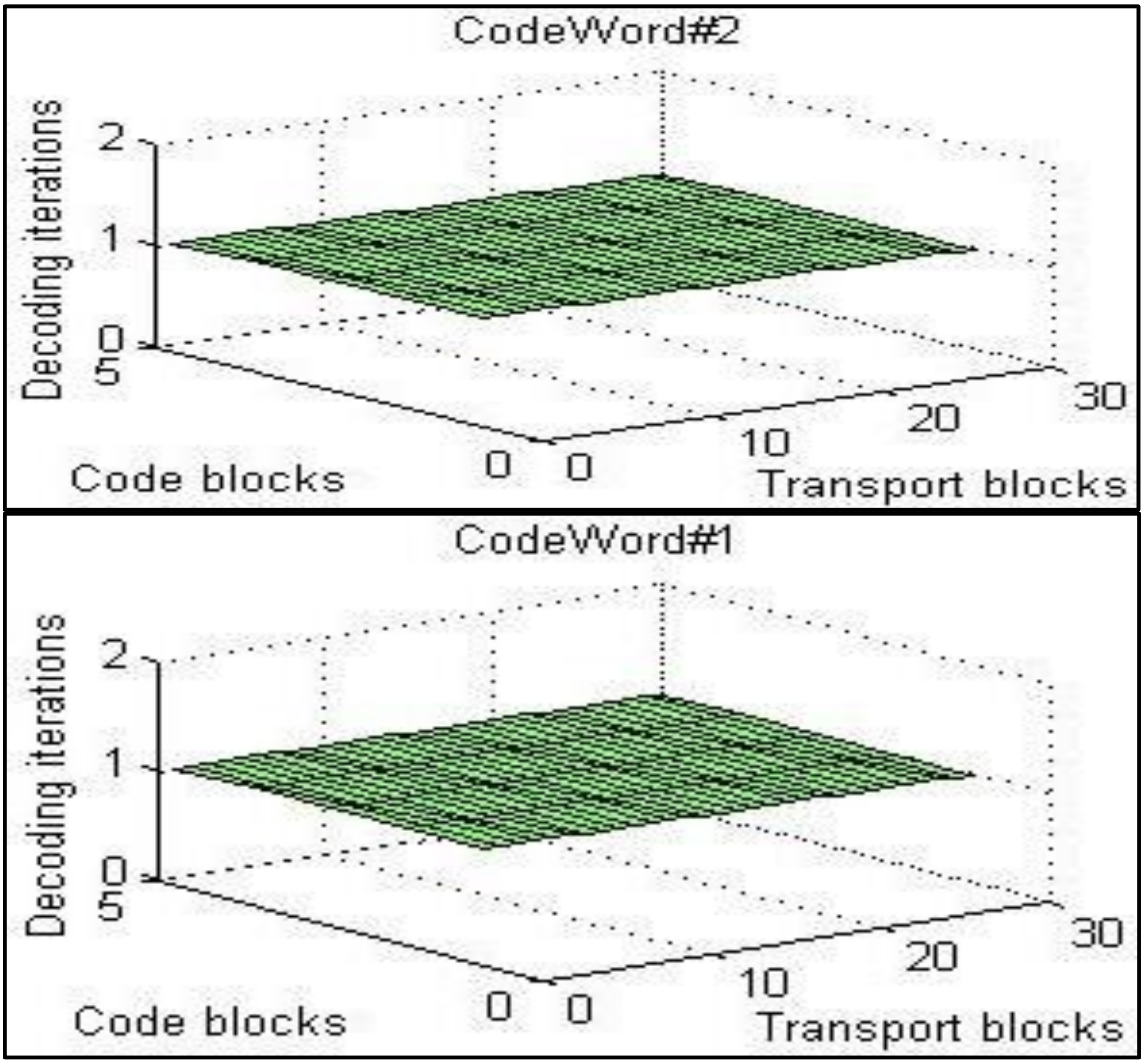


Figure 27: Scenario 1 Codewords

Figure (27) depict the received two codewords by the UE in three dimension diagrams, where it shows the number of transport blocks received viruses the number of transport code that have been segmented to and finally the number of iterations used in the turbo decoding. Because of the high SNR (20 dB) used in this scenario the decoder did not need to run the decoding iteration for error correction more than one time. And we can see from Figure (27) that the simulation model used only one iteration to retrieve the transport blocks (MAC layer blocks). In general Figure (27) shows that; under good SNR level the UE can get codewords with minimum errors and these errors are correctable hence higher data rate and higher throughputs. In this scenario, we chose (2×2) setting and we achieved 50.912 Mbps as the maximum data rate, so what will be the MIMO spatial multiplexing capacity if we change the antenna configuration to (4×4).

4.2.2 Second Scenario spatial Multiplexing.

For the second scenario we chose the following input parameters:

Input Parameter	Configuration	Input Parameter	Configuration
Channel BW	20 MHz	Coding Rate	1/2
Control Region	2	Fading Channel	EPA (0HZ)
Antenna Configuration	(4×4)	SNR	20 dB
Modulation Type	16 QAM	Decoding Iteration	6

Table 9: Scenario 2 Spatial Multiplexing Input Parameters

For this scenario, we made only one change and that for the MIMO configuration to be configured as (4×4), by this we will have for equal length data streams that will be transmitted independently over the MIMO channel. (Refer to Table 5 in Section 3.4).

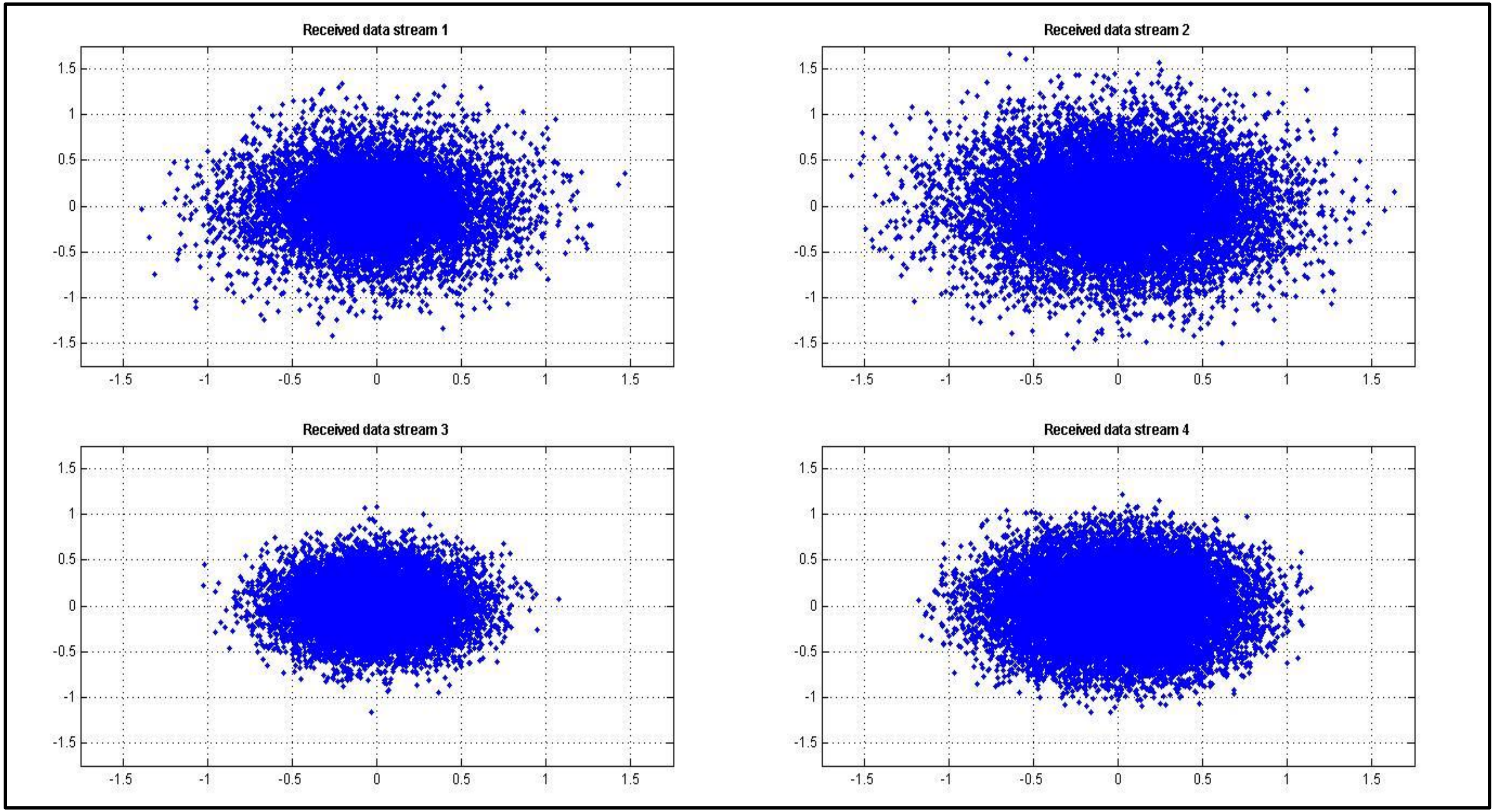


Figure 28: Scenario 2 Received Data Stream

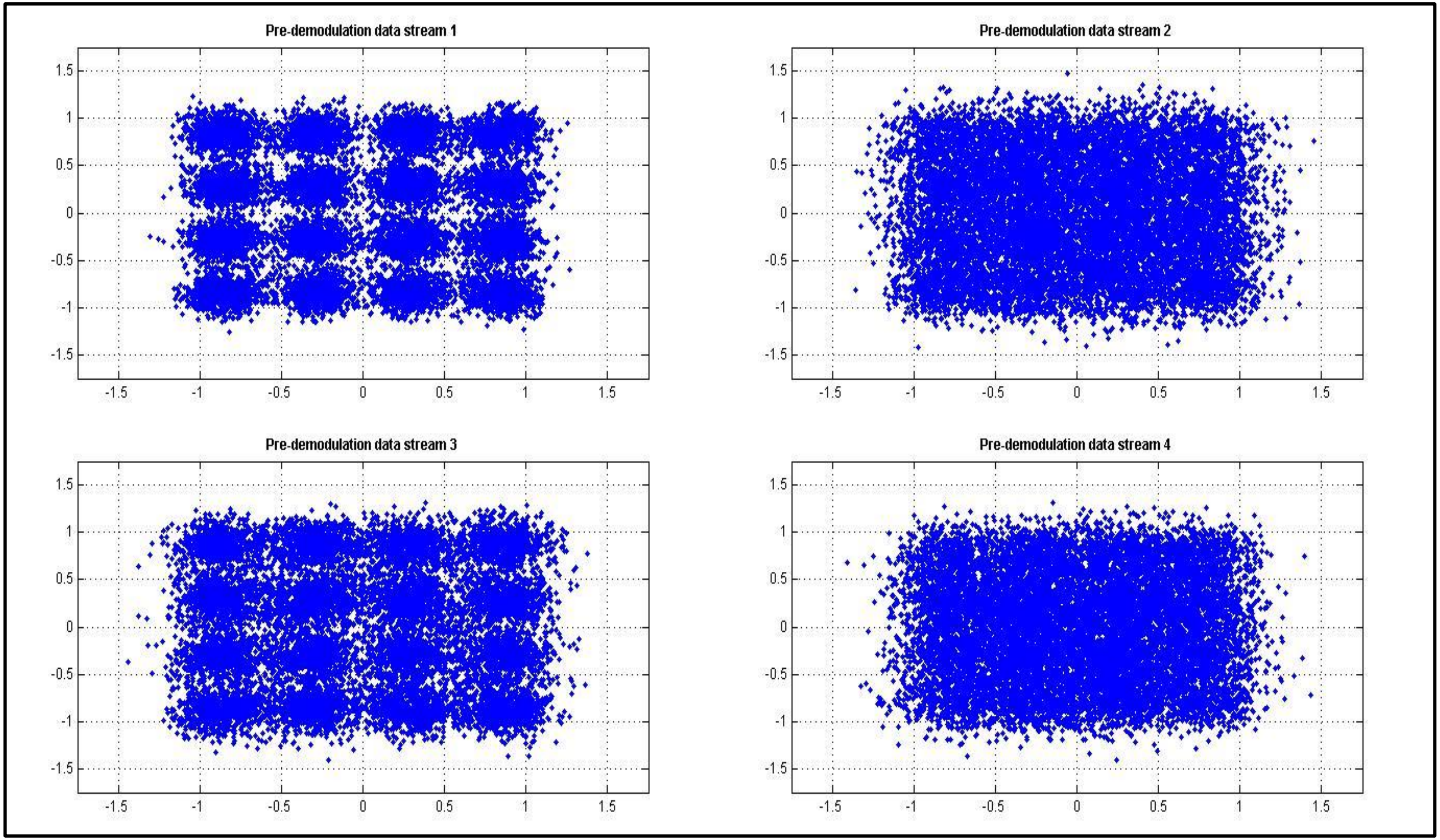


Figure 29: Scenario 2 Pre-Demodulation

Figure (28) and (29) depict the received data and the pre-demodulation data stream respectively, and as we mentioned earlier that each codeword must be split into two equal length data stream so we can transmit it over a (4×4) antenna configuration.(Table 5, section 3.4),by using this configuration we had four independent wireless propagation channels each had its own characteristic therefore each data stream subjected to different amount of frequency selectivity fading, where data stream 1 and 3 had effected by frequency selectivity fading less than data stream 2 and 4. Figure (29) shows that the pre-demodulation constellation of data streams 1 and 3 are more distinguishable than that of data stream 2 and 4, however all the data streams are suffering of (ISI) because $B_s > B_c$ and $T_s \ll \sigma_\tau$ still the same for each of the (4× 4) MIMO channel paths. Table (10) lists the collected results for scenario (2).

Output Parameter	Codeword One	Codeword Two
PDSCH BER	0.06239	0.08319
Codeword BER	0.02722	0.4944
Transport Block Error Rate (MAC Layer)	0.1	1
Maximum Data Rate Per Codeword (Mbps)	61.664	61.664

Table 10: Scenario 2 Results

From the results obtained we can see that the error rate increased in all levels, PDSCH, Codeword BER, and Transport Block error rate and that as we mentioned before is due to the multipath fading that the data streams subjected to. In MIMO spatial multiplexing, we just send the data streams independently through our antennas aiming to increase the data rate, but what about the throughput? The throughput decreased, and also the MIMO-OFDM channel depends on iterations for decoding plus sophisticated mathematical algorithms to retrieve the data streams. By using MIMO (4×4) we increased the data rate to (61.664 Mbps) that is true. However, the expenses for such increasing coming in account of the delay associated with retrieving the data. Which may lead to disconnecting the UE from the network, adding to that this scenario was based on high SNR (20 dB) and for such SNR there are many design issues must be taken in our consideration (Figure (1) section 1.2).

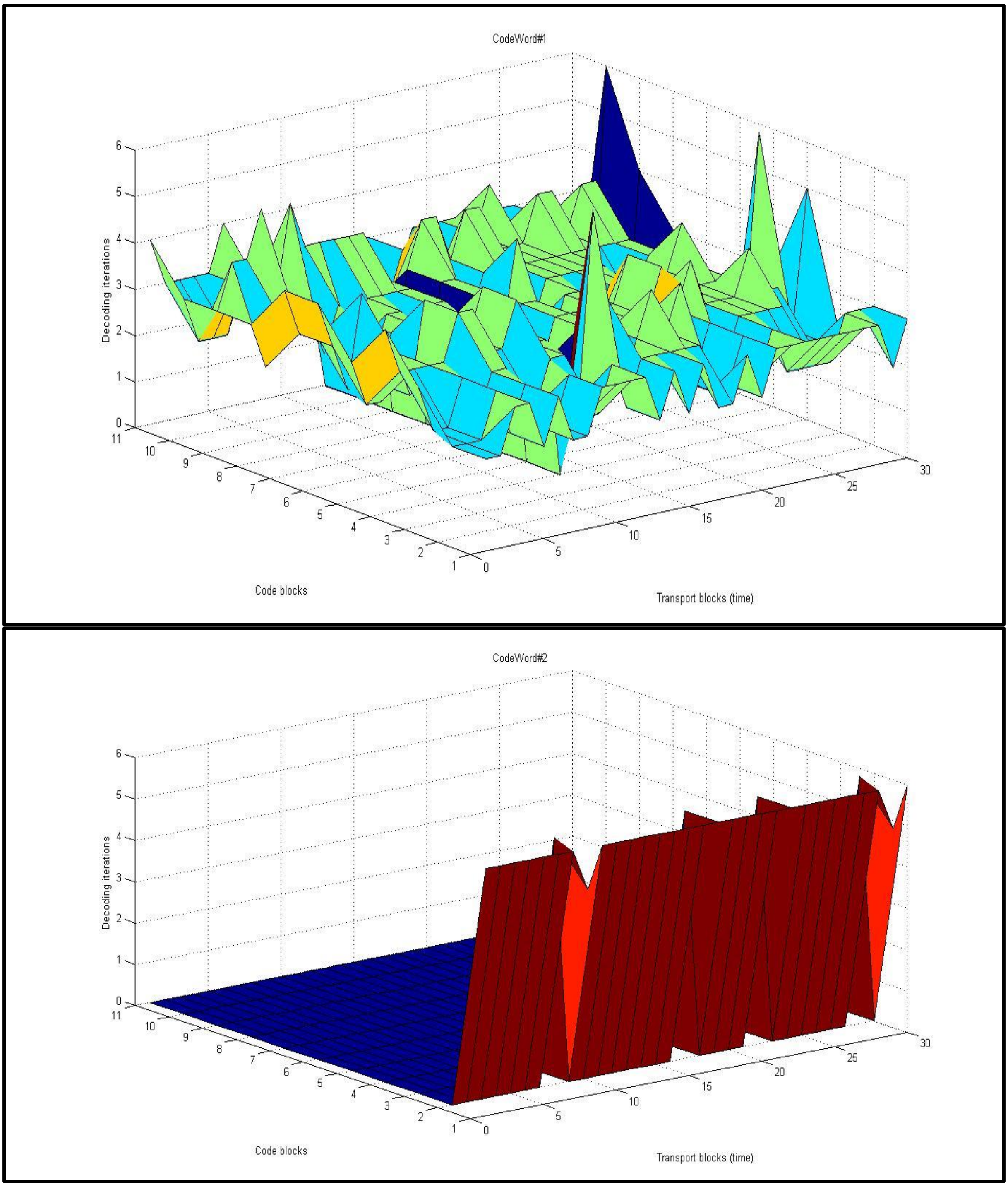


Figure 30: Scenario 2 Codewords

Figure (30) depict the codewords at the receiver (UE). And we can see the number of iterations how it increased comparing with scenario (1). And especially codeword one, and as we previously mention this is coming from the increased number of errors received from the PDSCH and accumulated back to the transport block (MAC blocks). It looks like a combat between the error correction and controlling algorithms and the increased errors due high data rate that been transmitted over a multipath fading channel. The question that is emerge here, Can we get any advantages from (4×4) MIMO spatial multiplexing under low SNR? We will investigate in the next scenario.

4.2.3 Third Scenario Spatial Multiplexing.

For our third scenario, we will reduce the SNR to 12 dB and investigate the MIMO performance. Most of the new LTE (RF) transmitters are transmitting on 40 W per each RF transmitter module which is equal to 16 dB However for better illustration we will set SNR to 12dB.

Input Parameter	Configuration	Input Parameter	Configuration
Channel BW	20 MHz	Coding Rate	1/2
Control Region	2	Fading Channel	EPA (0HZ)
Antenna Configuration	(4×4)	SNR	12 dB
Modulation Type	16 QAM	Decoding Iteration	6

Table 11: Scenario 3 Spatial Multiplexing Input Parameters

After running the simulation model for the given input parameters we got the following results.

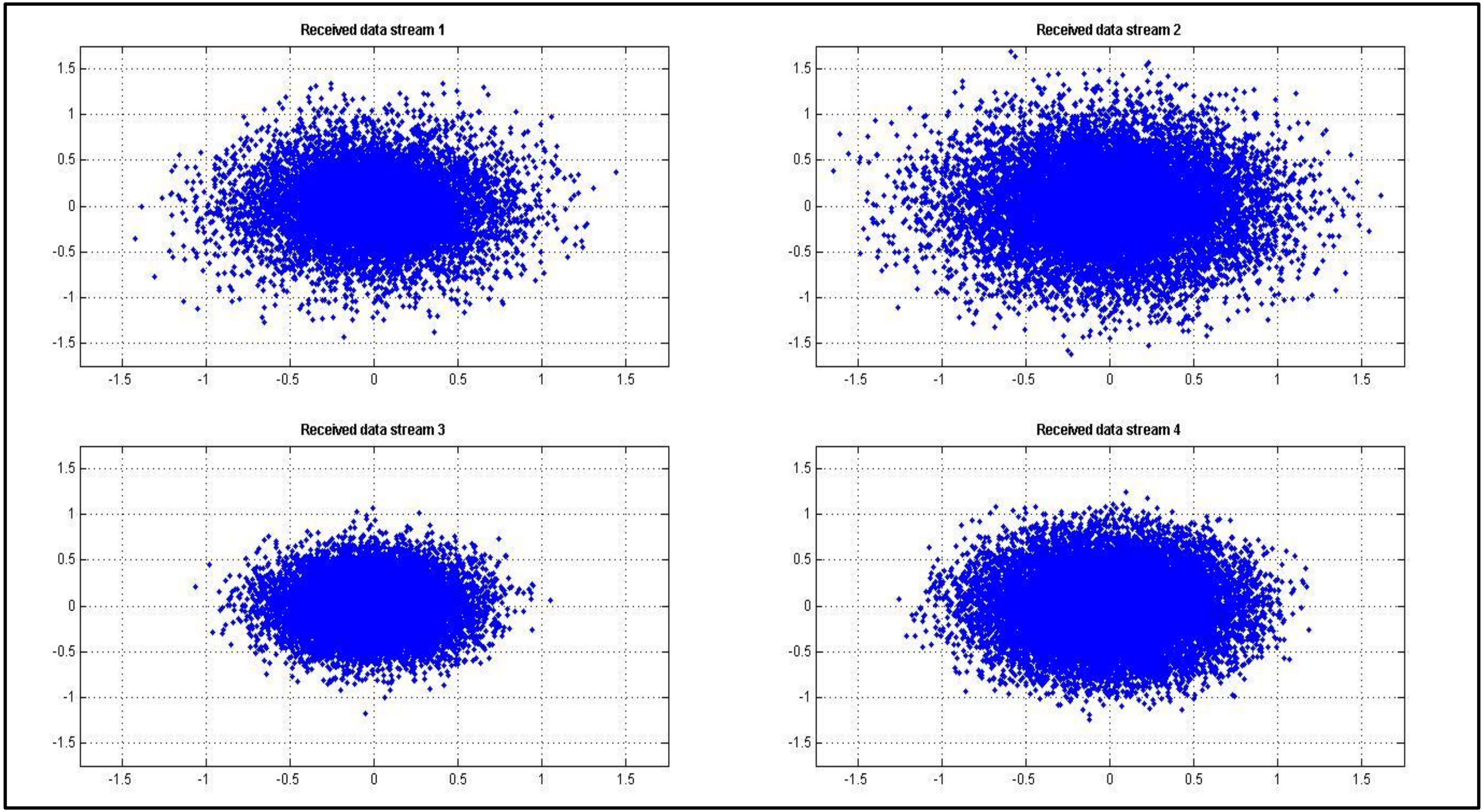


Figure 31: Scenario 3 received Data Stream

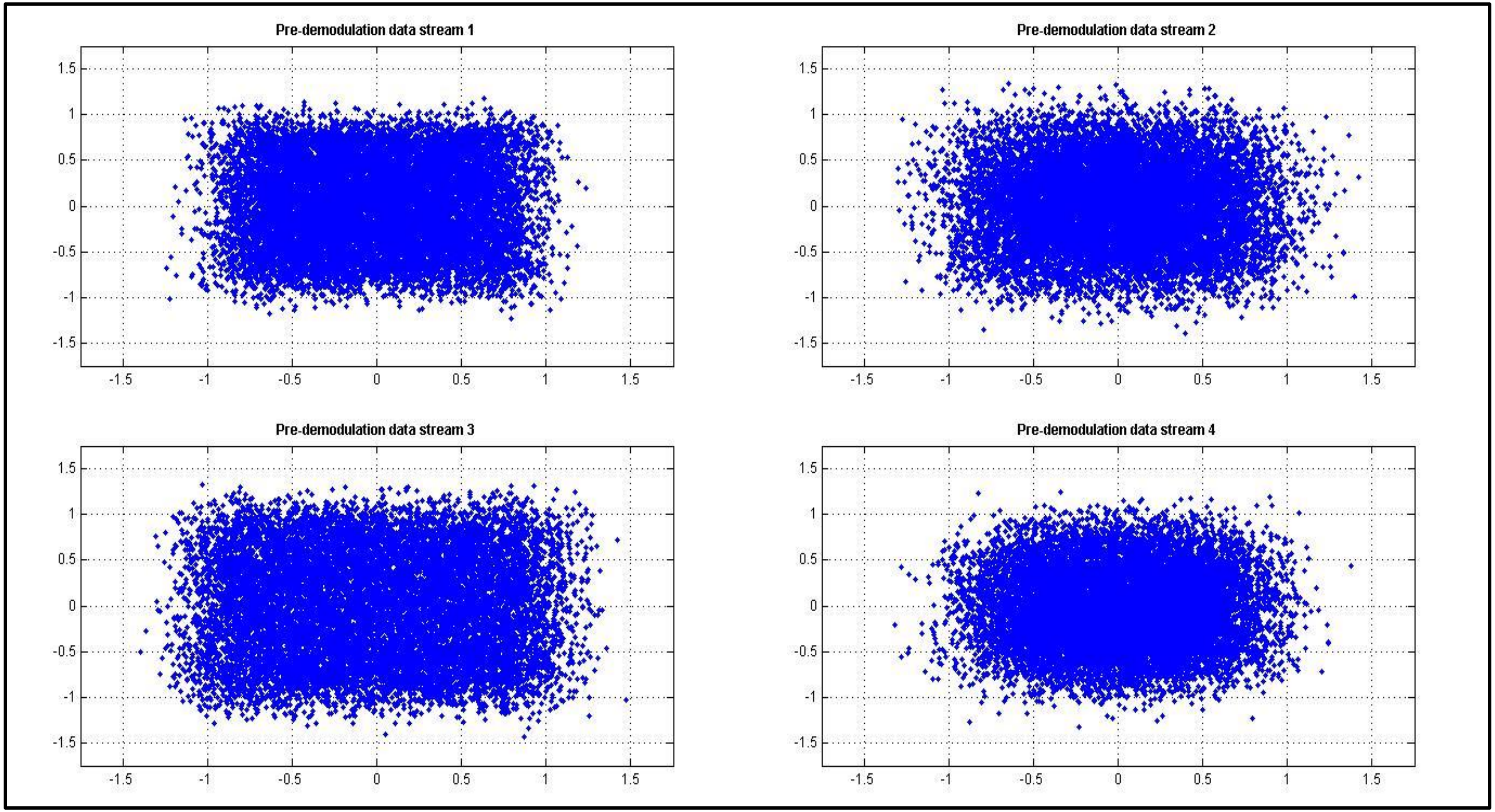


Figure 32: Scenario 3 Pre-Demodulation

As expected from reducing the SNR to 12 dB the constellation samples become more interfering and that what Figure (31) depict. Eventually, the pre-demodulation data stream also become denser in a way we cannot distinguish the 16 QAM constellation shape as figure (32) shows. And this all because the immunity against multipath fading will reduce as the SNR reduced. Recall that in (section 2.1.2) we discussed the power delay profile (PDP) of multipath signals arrived at different times at the receiver. Which makes them overlaps with each other and hence increasing the BER and this what we expected in scenario 3, however the data rate still 61.664 Mbps, but for sure the throughput decreased as the BER increased.

Output Parameter	Codeword One	Codeword Two
PDSCH BER	0.2092	0.2042
Codeword BER	0.5008	0.5004
Transport Block Error Rate (MAC Layer)	1	1
Maximum Data Rate Per Codeword (Mbps)	61.664	61.664

Table 12 : Scenario 3 Results

Table (12) shows the results obtained in scenario 3, and we can see clearly how the BER increased. So to overcome increasing in BER the spatial multiplexing MIMO increased the iteration of its Turbo encoding which add more delay to the system for retrieving the data streams. In spatial multiplexing, we discussed the rank index (RI) in (Section 3.2.3). Where (RI) is a feedback signal from the receiver back to the transmitter to tell how many layers that the receiver can distinguish to get the singular value decomposition (SVD) (Equation 3.4 in Section 3.2.3). And find a solution for the transmitted Matrix array vector, this feedback signal is based on sophisticated mathematical algorithm adopted by MIMO spatial multiplexing to maintain high data rate transmission. So to ensure reliable wireless communication we must take in consideration the system delay to retrieve the data streams. Recall that each resource block elements consisted of seven OFDM symbols that it is last for 0.5ms and 12 OFDM sub-carriers, so for such time frame structure we must insure smart network design to get the best SNR that is fulfil our expectations.

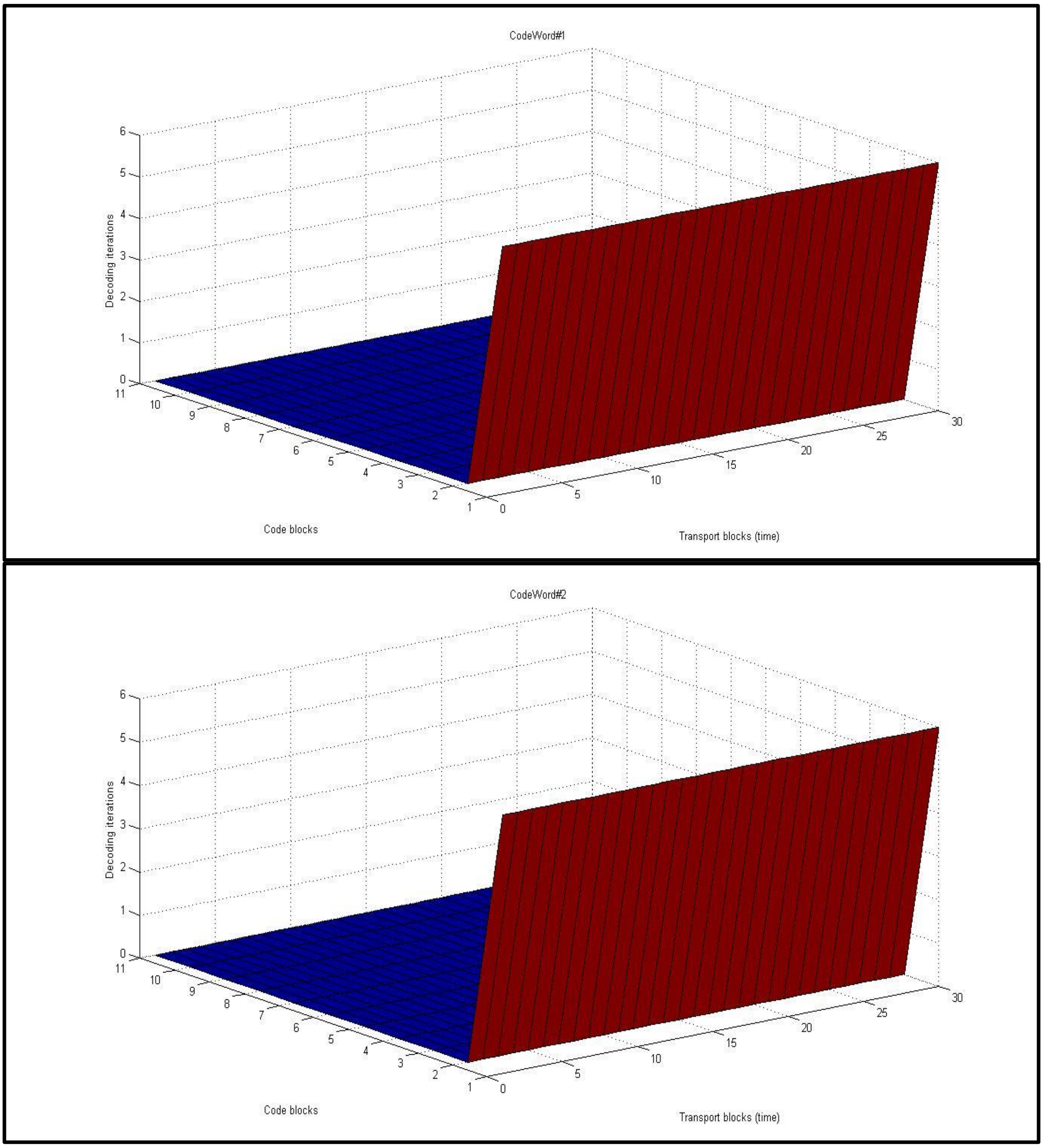


Figure 33: Scenario 3 Codewords

4.3 Testing MIMO Spatial Diversity.

First we will define the input parameters for our simulation model with its description.

Input Parameters	Description
Channel Bandwidth (MHz)	The available channel bandwidth are (1.4, 3, 5, 10, 15, 20) MHz, where according to the channel bandwidth we determine the number of Resource Blocks (Table (2) Section (3.2.2).
Control Region Size	Where the number of OFDM symbols per frame are chosen, the control region must be set for this model either 1,2 or 3 OFDM symbols for number of resource blocks greater than 10 (i.e. for channel bandwidth greater than 1.4 MHz). (Figure (17), (18) in section 3.2.2).
Number of Transmit Antenna	We had 2 and 4 to select for eNB transmitting antenna.
Number of Received Antenna	We had 1, 2 and 4 to select for UE received antenna.
PDSCH Modulation Type	QPSK, 16 QAM and 64 QAM
MIMO Rayleigh Fading Channel	Here we had two options either we select Frequency-Flat static, or User- Defined.
Maximum Doppler Shift.	we will take in consideration the movement of the (UE) And the effect of the Doppler effect and for that we had from LTE standards we had, Extend Pedestrian A model (EPA), Extend Vehicular A model (EVA), for our model we will switch between these types of fading channels. (refer to Section 2.1.2) I will chose (EPA= 0Hz) for our simulation
Path Delay Vector (Ts).	It is a vector of integers specifying the path delays in multiples of the channel sample time. The length of this parameter indicates the number of multipath channels modelled for the fading channel For our simulation I will chose five elements for the path delay vector [0 5 8].
Average Path Gain Vector (dB).	It is a vector of path gain values in dB The length of this parameter must be the same as the length of the path delay parameter.
Correlation Level	Correlation between antennas is primarily function of space between the antennas and the polarization of the antennas. For our simulation we will assume that the correlation is low and this is mean that the antennas are well separated 10λ and with different polarization.
Signal to Noise	The most important parameter that we will change it over a range of different SNR values.
Number of LTE sub-Frame	According to standards we had 20 Sub-Frames in 10ms, so I will double it to (40 sub-frames) for higher data rate.

Table 13: MIMO Spatial Diversity Input Parameters Description

4.3.1 First Scenario Spatial Diversity.

Following Table (14) list the input parameters for first scenario:

Input Parameter	Configuration	Input Parameter	Configuration
Channel BW	20 MHz	PDSCH Modulation	16 QAM
Control region	2	Maximum Doppler Shift (EPA)	0Hz
Number of Transmit Antenna	2	Path Delay Vector (Ts)	[0 5 8]
Number of Receive Antenna	2	Average Path gain Vector	[0 -3 -6]
SNR (dB)	20 (dB)	Correlation Level	Low
Number of Sub-Frame	40		

Table 14: Scenario 1 Spatial diversity Input Parameters

To make a realistic comparison between spatial multiplexing and spatial diversity we will choose the same channel bandwidth with same control region as well as the same modulation scheme. After running the model for the given parameters, we get the following results:

Parameter	Result
Number of Bits	2.1 MBits
Number of Errors	68
Bit Error Rate (BER)	$3.2332\ e^{-05}$

Table 15: Scenario 1 Spatial Diversity Results

From the results obtained we can conclude that spatial diversity had better BER comparing with that of spatial multiplexing. However, the concept of spatial diversity does not concern about the data rate. As much as to increase the channel gain by transmitting the same data stream over diverse antennas with the help of Space Frequency Block Coding (Section 3.3) to encode the data over the diverse antennas. Figure (34) depict the two Post-OFDM received data from the same input data stream.

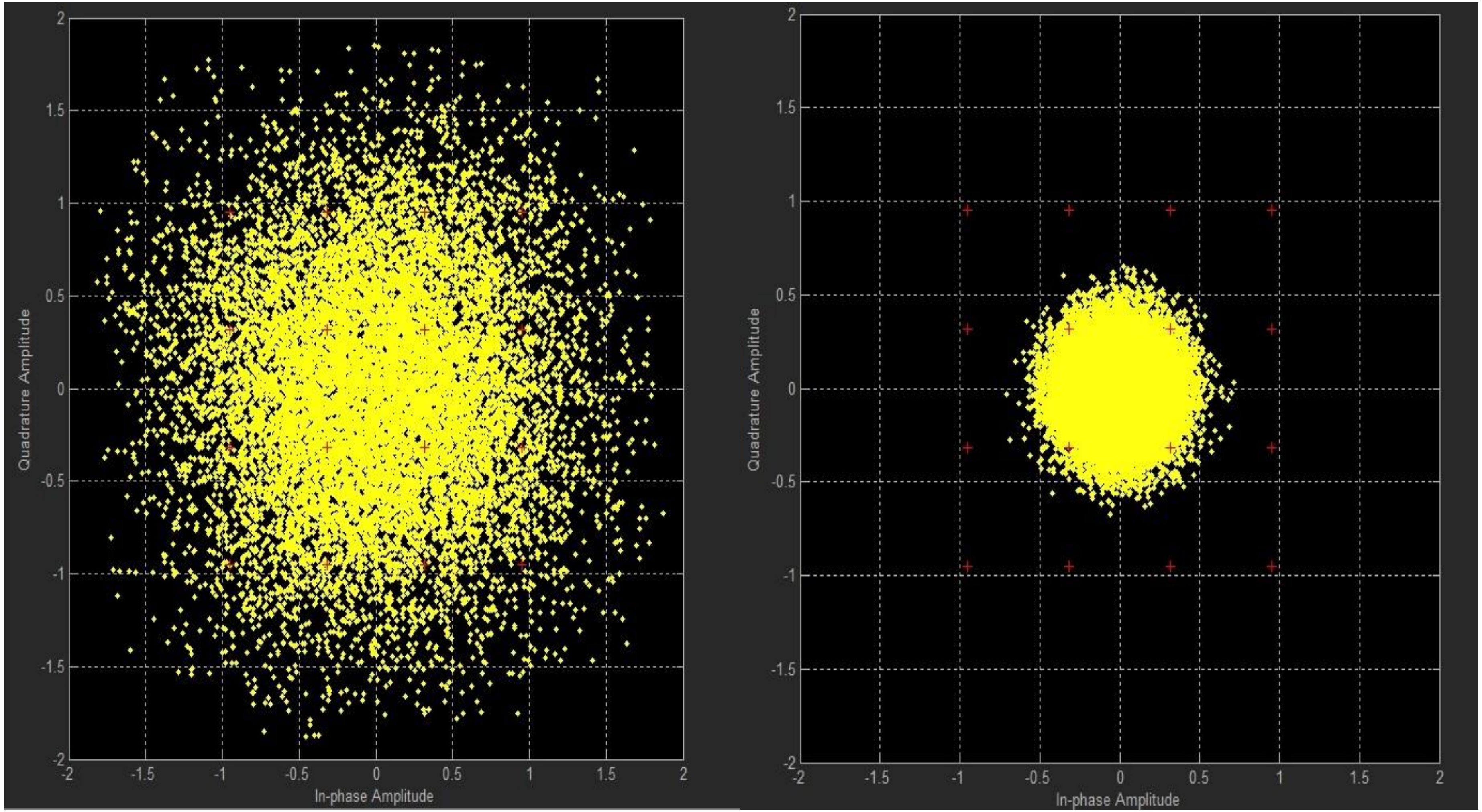


Figure 34: Scenario 1 Spatial Diversity Received Data Stream

Figure (34) shows the two received data after the OFDM demodulation. And we can see how multipath fading effected the two data stream due to delay spread and different power delay distribution (PDP) of each path. However, we know from Section 2.1.2, that for non-frequency selectivity channel we must have $B_s \ll B_C$ *and* $T_s \gg \sigma_\tau$ and here the importance of diversity MIMO is coming. Whereby sending multiple copies of the signal through diverse antennas, MIMO diversity convert the Rayleigh fading in to stable AWGN-like. Recall that MIMO spatial diversity sending the same copy of the signal over diverse antenna where the data rate is not changed. Unlike spatial multiplexing where different data stream are carrying through the MIMO channel (higher data rate), and this makes spatial diversity capable of fulfilling the equation$B_s \ll B_C$ *and* $T_s \gg \sigma_\tau$. Figure (35) shows the two data streams after combining.

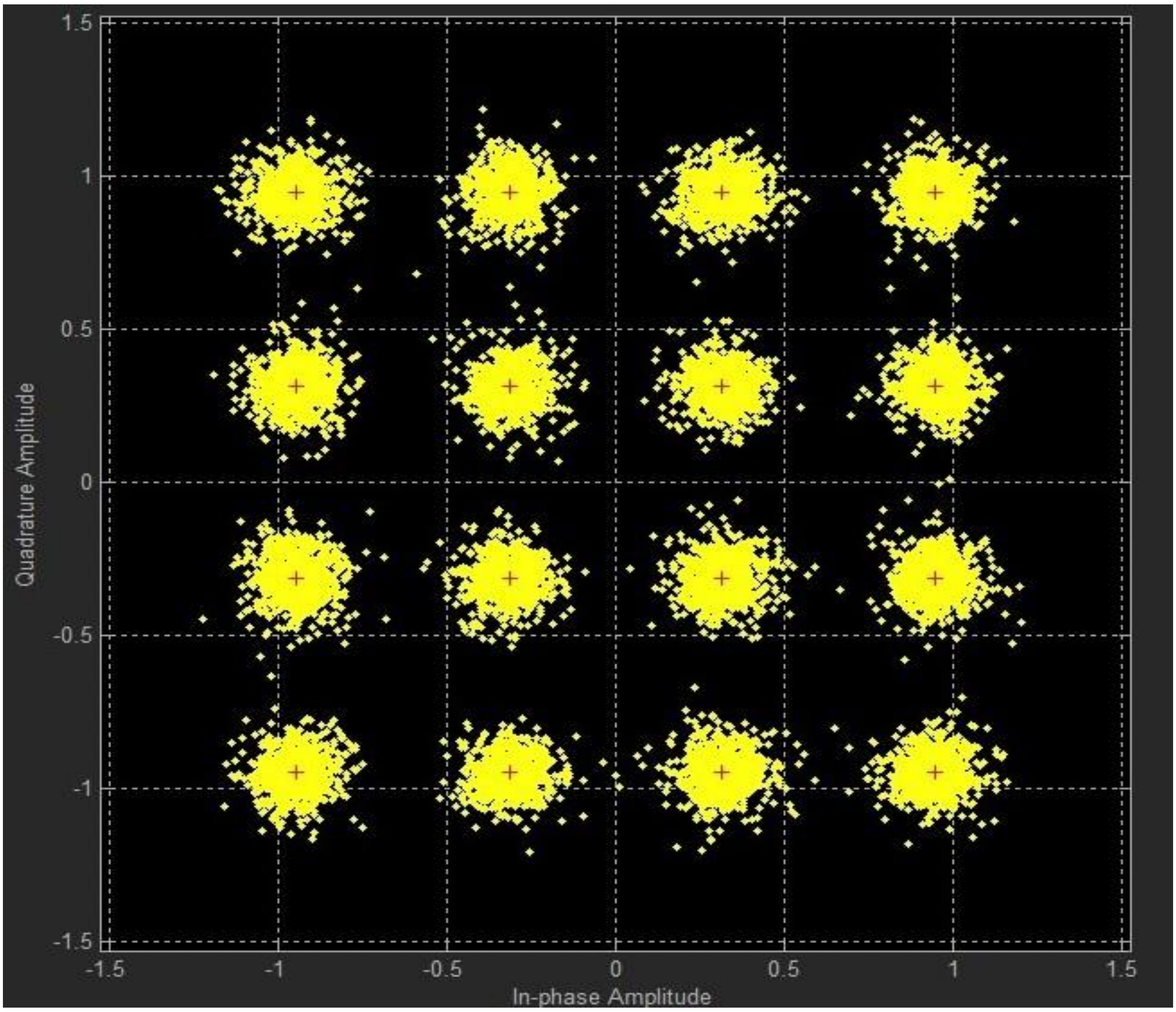


Figure 35: Scenario 1 Spatial Diversity Combined Data Stream

4.3.2 Second Scenario Spatial Diversity.

In this scenario, we will push the limits of spatial diversity by increasing the data rate to be transmitted over the channel by changing the modulation scheme, increasing the number of sub-frames, and increase the control region to check the performance of the system.

Input Parameter	Configuration	Input Parameter	Configuration
Channel BW	20 MHz	PDSCH Modulation	64 QAM
Control region	3	Maximum Doppler Shift (EPA)	0Hz
Number of Transmit Antenna	2	Path Delay Vector (Ts)	[0 5 8]
Number of Receive Antenna	2	Average Path gain Vector	[0 -3 -6]
SNR (dB)	20 (dB)	Correlation Level	Low
Number of Sub-Frame	400		

Table 16: Scenario 2 spatial Diversity Input Parameters

The simulation results after running the model is listed in table (17) below:

Parameter	Result
Number of Bits	28.667 Mbits
Number of Errors	105807
Bit Error Rate (BER)	0.0036908

Table 17: Scenario 2 Spatial Diversity Results

As expected, we increased the number of transmitted bits over the MIMO spatial diversity channel by increasing the number of sub-frames. (Referring to Section 3.2.2 Figure (17)), each sub-frame has seven OFDM symbols each with 2048 FFT bits separated by Cyclic Prefix of 144 FFT bits except for the first cyclic prefix which is of 160 FFT bits. So one sub-frame is consisted of $(7\times 2048) + (6 \times 144)\ CP + (160\ )first\ CP$, and that gives us 15360 FFT bits for standard one LTE sub-frame. So for our simulation we chose 400 sub-frame to transmit, and this is equal to (400×15360) which is equal to 6.1Mbits. adding to that by changing the modulation rate to 64 QAM we increased the data rate. Finally, the number of the control region which increase the number of OFDM symbols per sub-frames. Hence, increase the total bits that we calculated above per sub-frame.

Continuing the same object, from the results obtained the spatial diversity channel had transmitted 28.667 Mbits with error rate of (0.009129). Which is a high error rate, and we can see the effect of multipath fading on the received data streams especially when we increased the data rates. Figure (36) depict the received data streams.

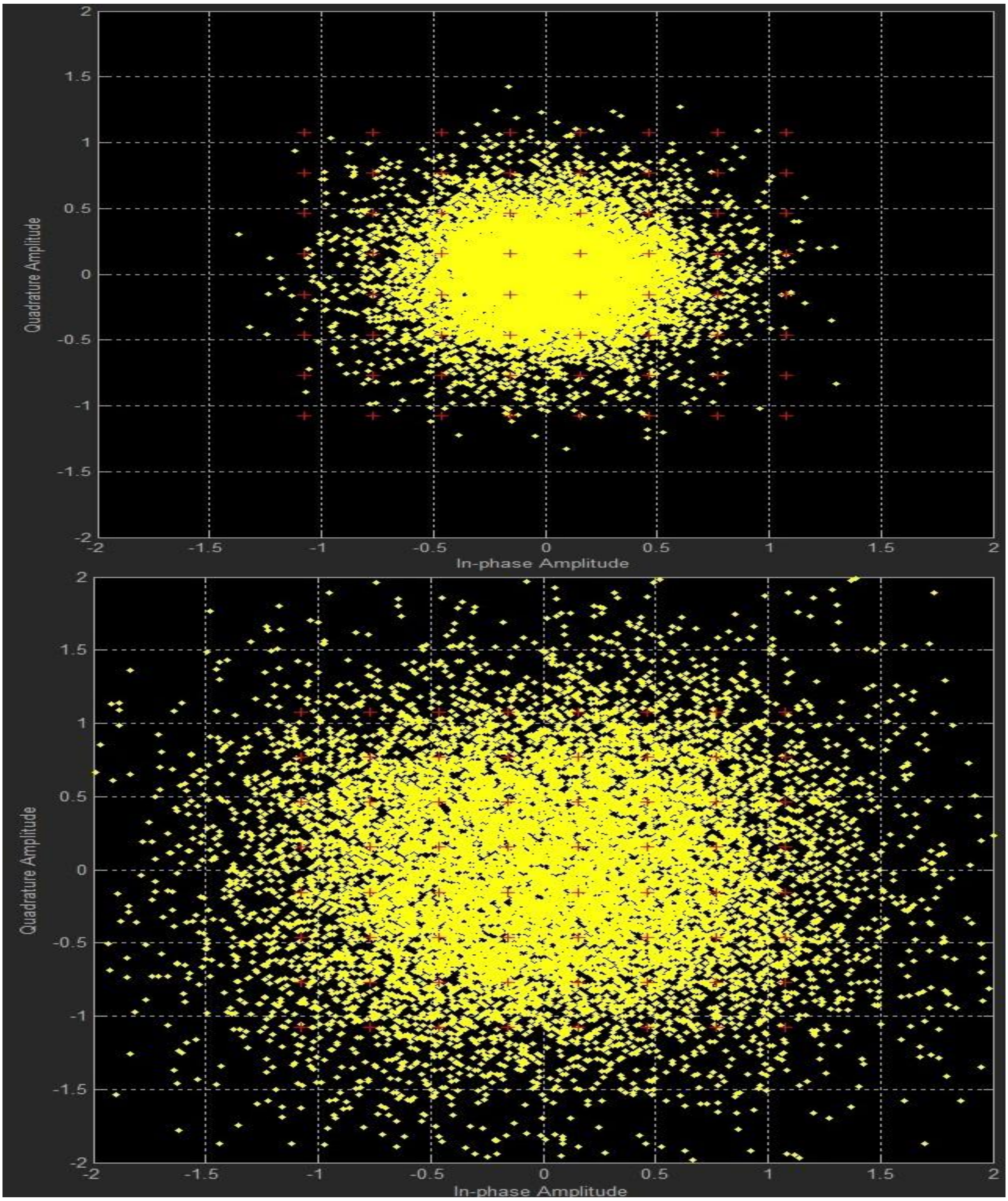


Figure 36: Scenario 2 spatial Diversity Received Data

Both data streams must be In-Phase before interring the combiner. Where different delay adjustment are applied to make the data streams In-phase before interring the combiner to combining them, however here the delay adjustment could not effort much to overcome the delay spread RMS induced from the fading path. So to overcome this issue we need to increase the number of MIMO antennas in both transmitter side and receiver side. And that what we will check in our next scenario, as regard this section Figure (37) shows the two combined data stream and it is evident from the figure that the combined data are suffering from (ISI) due to the channel frequency fading.

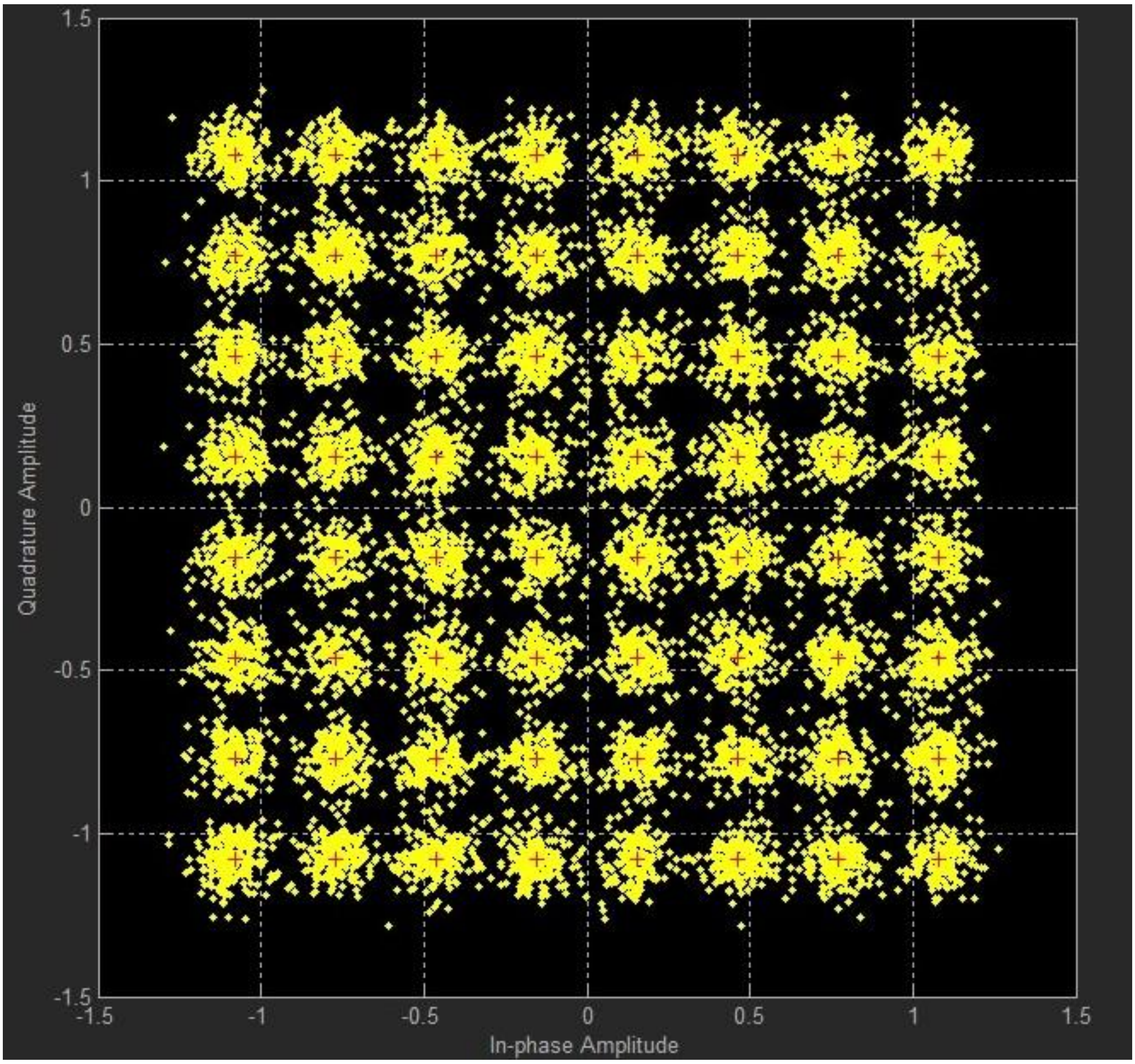


Figure 37: scenario 2 spatial diversity Combined Data Stream

4.3.3 Third Scenario Spatial Diversity.

The task here is to show if MIMO diversity scheme can provide better BER by increasing the number of transmitted and received antennas to (4×4) for the same input parameters provided in scenario 2.

Input Parameter	Configuration	Input Parameter	Configuration
Channel BW	20 MHz	PDSCH Modulation	64 QAM
Control region	3	Maximum Doppler Shift (EPA)	0Hz
Number of Transmit Antenna	4	Path Delay Vector (Ts)	[0 5 8]
Number of Receive Antenna	4	Average Path gain Vector	[0 -3 -6]
SNR (dB)	20 (dB)	Correlation Level	Low
Number of Sub-Frame	400		

Table 18: Scenario 3 Spatial Diversity Input Parameters

Table (19) list the output results of scenario three.

Parameter	Result
Number of Bits	27.71 Mbits
Number of Errors	52613
Bit Error Rate (BER)	0.0018985

Table 19: Scenario 3 Spatial Diversity Results

From the first glance, we may say that the BER is better than that of the (2×2) MIMO configuration. However, it is not like that if we look at the number of bits that had been transmitted over the spatial diversity antenna in (4×4) configuration we will see that is less than that of (2×2) configuration (refer to Table (17) in scenario two). So we can say that we did not get that promising output from (4×4) configuration.

And the reason for that as usual is the frequency selectivity fading, although we increased the number of transmitted antennas as well as the received antennas to (4×4), but actually we increased the probability density function of the Rayleigh fading component of NLOS (section 2.1.2). Figure (38) below shows the received data stream from the four transmitted antennas.

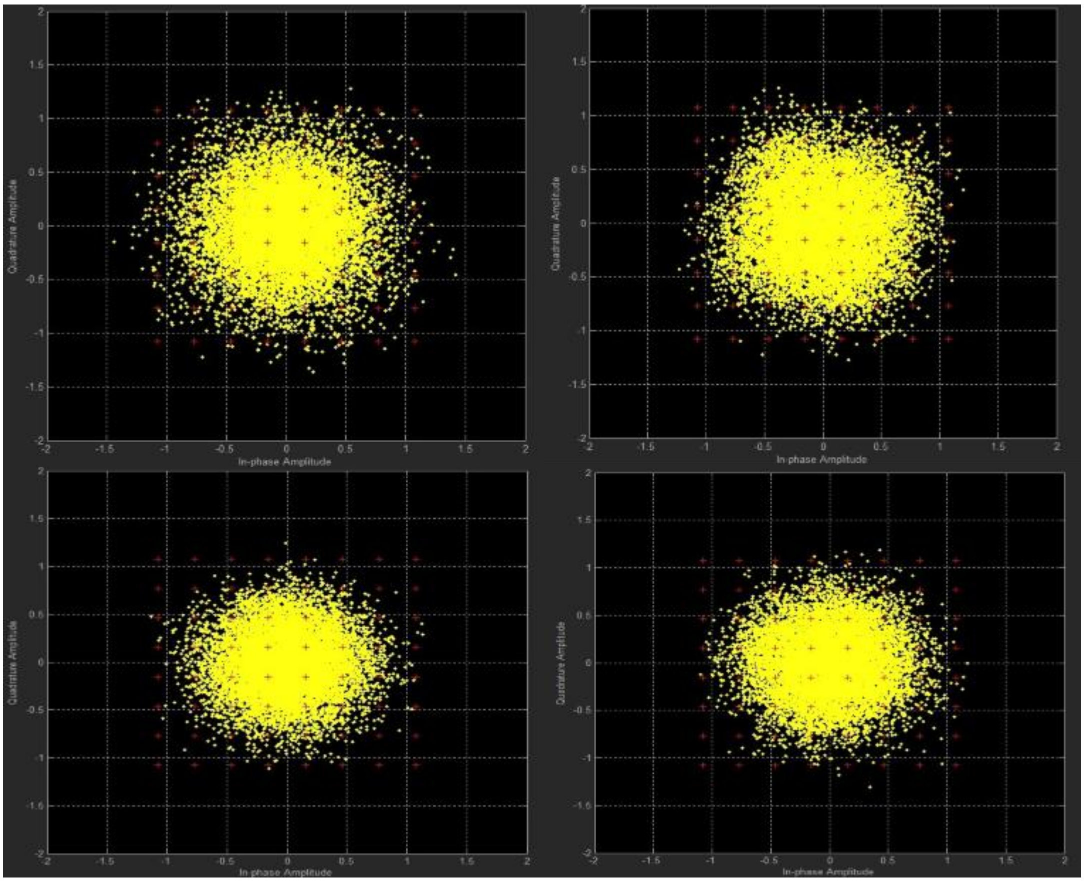


Figure 38: Scenario 3 Spatial Diversity Rx. Data

As we mentioned previously that these four data streams must be In-phase so the combiner can combing them to get the maximum signal level from these multipath diverted data, but as it is expected it will not be much better than the results obtained for (2×2) configuration.

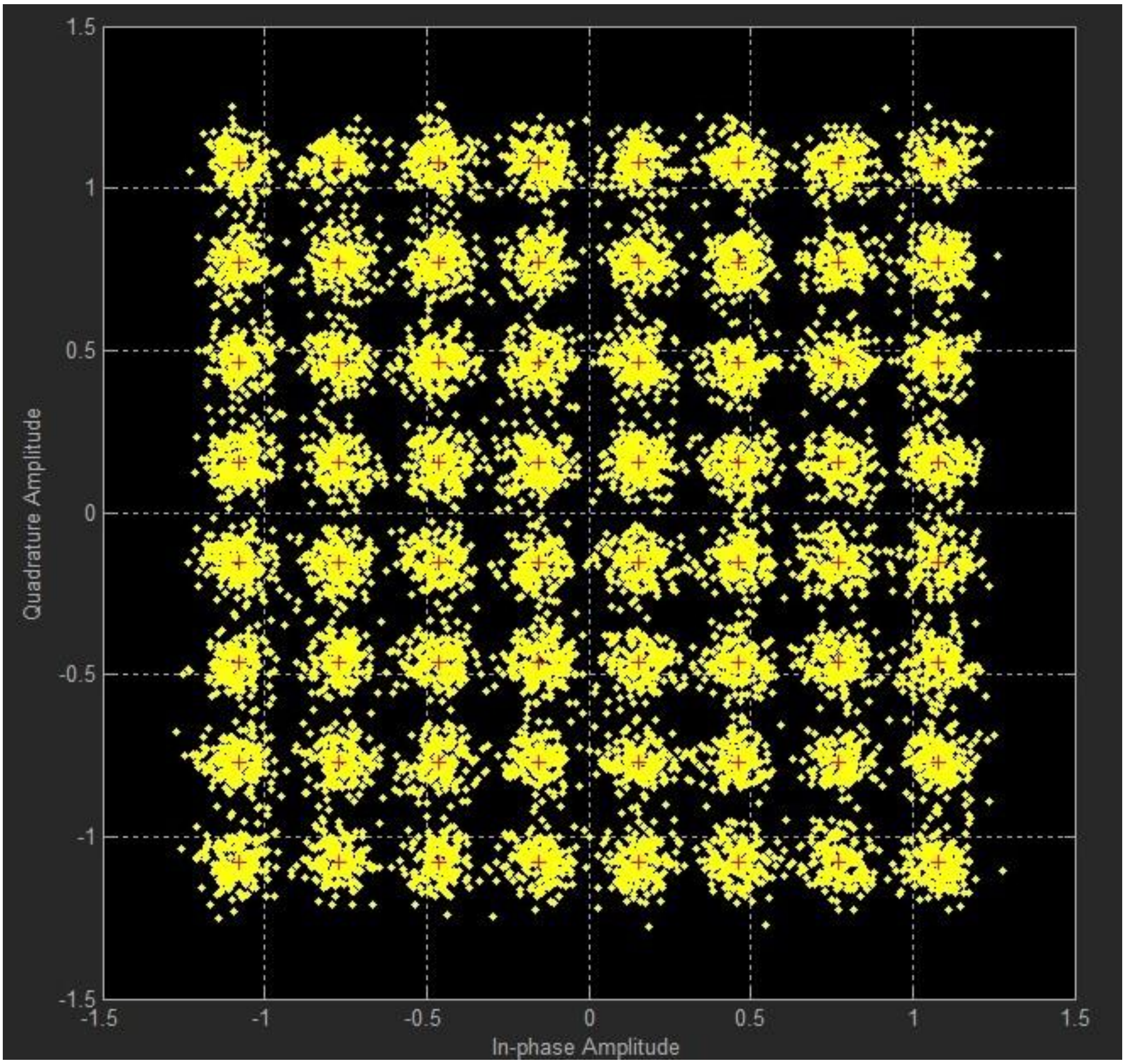


Figure 39: scenario 3 spatial Diversity combined Data Streams

4.3.4 (Special Case) Scenario Four.

In this scenario, I would like to appreciate the diversity gain of MIMO spatial diversity, where we transmit or data over two transmit antennas and received through four received antennas the other parameters I will leave it unchanged.

Input Parameter	Configuration	Input Parameter	Configuration
Channel BW	20 MHz	PDSCH Modulation	64 QAM
Control region	3	Maximum Doppler Shift (EPA)	0Hz
Number of Transmit Antenna	2	Path Delay Vector (Ts)	[0 5 8]
Number of Receive Antenna	4	Average Path gain Vector	[0 -3 -6]
SNR (dB)	20 (dB)	Correlation Level	Low
Number of Sub-Frame	400		

Table 20: Spatial Diversity Special Case Scenario

Table (21) shows the output results of scenario four:

Parameter	Result
Number of Bits	28.66Mbits
Number of Errors	47692
Bit Error Rate (BER)	0.0016636

Table 21: Spatial Diversity Special Case Results

Table (21) shows the expected performance of spatial diversity MIMO channel to overcome the small-scale fading channel especially Rayleigh fading. Where by decreasing the number of transmitted antennas, we decreased the number of multipath channels and the received diverse antenna get the maximum advantages from the multipath signals received, for the results we can see how the throughput increased compared with scenario three.

Also, we can observe that the BER decreased compared with scenario three. So we can achieve maximum performance from MIMO spatial diversity by increasing the number of diverse received antennas and reduce the number of transmit antennas. So that we reduce the effect of multipath fading effect.

Figure (40) depict the four data streams received by diverse received antennas, and as we previously mentioned the receiver will apply delay adjustment to these streams to makes them In-Phase before interring the combiner to retrieve the original signal with better quality.

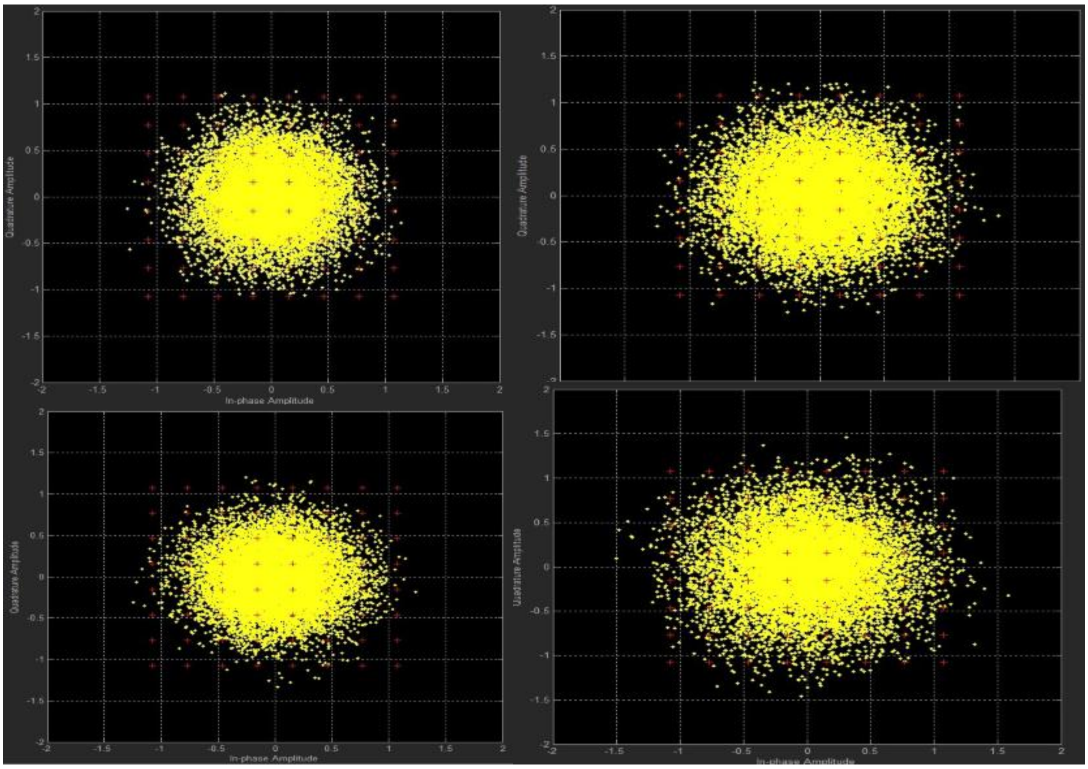


Figure 40: Scenario 4 spatial diversity Received Data Stream

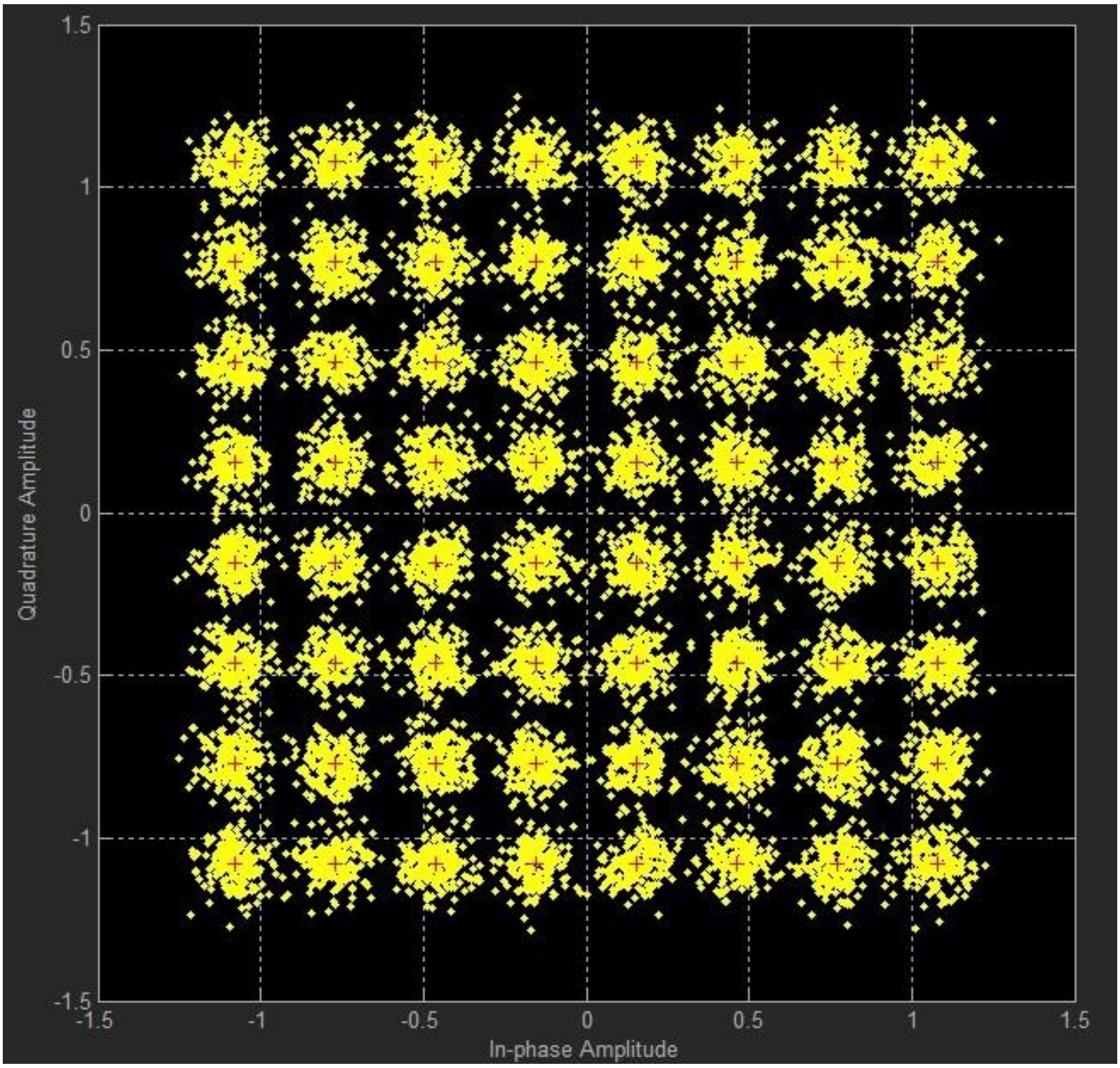


Figure 41: Scenario 4 Spatial Diversity Combined Data Streams

Figure (41) shows the constellation diagram of the received data stream after the combiner. Hence by increasing the number of received antennas at the receiver we increased the diversity gain and the throughput while the BER decreased. Keeping in mind that we reduced the number of transmit antennas to reduce the number of multipath fading channel.

Chapter Five (Critical Evaluation).

The aim of this study is to analyse and examine two types of MIMO systems. The Spatial Multiplexing MIMO Channel and the Spatial Diversity MIMO Channel. And how to build an algorithm for combining both systems together. So that the wireless network element can get the best advantages of these two system by switching between them under different propagation circumstances, and that is considered to be Self-Organizing Network. So to do that we must first have an understanding about the propagation characteristic of a wireless channel (Chapter 2). And the primary technologies that recently adopted to get the maximal gains from MIMO system; such as OFDM and Turbo Coding (Chapter 2 and 3) which they are used in conjunction with MIMO system to improve the system performance parameters such as capacity, BER, delay… etc. The design specification of the MIMO channel (Chapter 3) are based on MATLAB Simulink simulation and to do that we need to translate the standards provided by LTE 3GPP Release 10 into MATLAB functions. The Simulink model reflects the real world scenarios into the simulation workspace. These functions that I used is built by Mathwork team for researchers and students to investigate LTE PDSCH with Spatial Multiplexing and LTE PDSCH with Spatial Diversity. So I used it to analyse the MIMO system. However, to show what is Self-Organizing Network. We may need more advanced software simulation programs that can show how the network elements (eNB) take decisions for Handover UE due to different network status or how they communicate between each other to increase the capacity and coverage area of the network. Also, as regard our research, changing the MIMO system from Spatial Multiplexing to Spatial Diversity, which all considered as (Self-Optimizing). But with the absence of such software the best alternative is MATLAB with a Soft define Radio Kit (SDR) to simulate the real time scenario. However, that needs a lot of time to master it, so we left with the provided MATLAB Simulink model to simulate only one part of Self-Optimizing, and that by building an algorithm for self-optimize MIMO system.

The results that we obtained from running MATLAB models are reliable, and the outcomes meet our expectations. Where we described all the relevant background information and mathematical representation for the essential components involved in building the MIMO system, with the aim of graphs and flowcharts (Chapter 3 and Chapter 4). Also, I provide the necessary illustration for all the input parameters and why we are using these particular input parameters (Chapter 4) and what is the expected output of these input parameters with the aim of MATLAB graphs and communication tool box provided from Mathworks. Adding to that, I used MATLAB codes to illustrate any necessary mathematical formula or technique related to our study.

The random nature of wireless channel response to different signals frequencies under different environmental situations makes the calculation of various parameters based on a statistical distribution. As the arrival of signals to the receiver, side is under different time and with different gain. And for that reason we used MATLAB to generate random vector matrices to represent the propagated signal through MIMO channel. Also, I support the analysis a wireless channel characteristic with a mathematical equation that explain the nature of these random variables (Chapter 2). The main parameter that we used to test the effects of these random variables on the performance of MIMO channel is (SNR). That is not mean the other parameters are not necessary, but SNR is more related to the network design. So to get good SNR you must have a rigorous network design (Chapter 1, Figure 1). And by this we meant a rigid radio network dimensioning covering all the relevant parameters like Coverage, Capacity, Frequency Resources, etc. Otherwise, even if you had implemented the most advanced technology in your network, it will not give the promises outcome. SNR relates the eNBs that sharing the same geographical coverage area together. By monitoring the SNR on periodic intervals, the eNBs can predict in advance the network changes. Then send update messages to the other eNBs to readjust their settings including, for example, the MIMO configuration from spatial multiplexing to spatial diversity, and this is Self-Optimization, which is part of Self-Organizing network. I divided my test mythology into three scenarios, and as I previously said, I analysed the MIMO performances under different SNR level. I also, changed the Modulation scheme, the Antenna configuration, and control region. For both MIMO schemes, I always started with moderate scenario to investigate the system behaviour under normal conditions. Then gradually I began to change the parameters mentioned above to get higher data rate and check the system performance with the new input parameters and compare the results between the scenarios (Chapter 4). For example, in spatial multiplexing the input parameters for the first scenario (Table 7, Section 4.2.1) was as follow:

Input Parameter	Configuration	Input Parameter	Configuration
Channel BW	20 MHz	Coding Rate	1/2
Control Region	2	Fading Channel	EPA (0HZ)
Antenna Configuration	(2×2)	SNR	20 dB
Modulation Type	16 QAM	Decoding Iteration	6

Then for the second scenario (Table 9, Section 4.2.2) of spatial multiplexing, we changed only the antenna configuration to see how the system will interact with the changes. Then in the last scenario (Table 11, Section 4.2.3) we take the extreme configuration by changing the SNR, Modulation scheme and the control region. And the reason for doing that as we mentioned is to increase the data rate and see how the system tolerate such condition. You may notice that two input parameters I did not change, and that is the Decoding Iteration and the Fading Channel Characteristic. The reason for that I chose only six iterations was because of the execution time. Where it is increases dramatically as we increased the number of iterations adding to that, for personal PC it will overload the processor, and it may lead to crash or in the best scenario gave unrealistic results. However, the chosen number of iterations was more than enough to appreciate the turbo decoding implemented in the model (Section 3.2.1). As regard the channel fading characteristic, the model was providing different options. Each option had a different impact on the fading channel hence different bit error rates. But I chose (EPA 0Hz) only. This parameter is for the Doppler Effect and as I am interesting to investigate the system performance in a more NLOS environment and to ensure that the channel characteristic is following a Rayleigh distribution for NLOS environment (Equation 2.11, Section 2.1.2).

And by the same reason I took the same Doppler Effect for spatial diversity input parameters. Continuing to spatial diversity, I adopted the same strategy for sorting the scenarios as for spatial multiplexing. However, you may notice that there are some settings I keep it without changing (Table 14, Section 4.3.1). Below is the input parameters for the first scenario of spatial diversity.

Input Parameter	Configuration	Input Parameter	Configuration
Channel BW	20 MHz	PDSCH Modulation	16 QAM
Control region	2	Maximum Doppler Shift (EPA)	0Hz
Number of Transmit Antenna	2	Path Delay Vector (Ts)	[0 5 8]
Number of Receive Antenna	2	Average Path gain Vector	[0 -3 -6]
SNR (dB)	20 (dB)	Correlation Level	Low
Number of Sub-Frame	40		

The unchanged parameters are the Path Delay Vector, Average Path Gain Vector and the Correlation level. Regarding the path delay vector is an integer vector represent the delay that we multiply by the channel samples to model the effect of multipath channels. Where each component of the vector is representing the channel delay of the I'th path channel, and it is associated with an average path gain for each one of these I'th channel paths (Equation 2.4, Section 2.1.2). So as far as we considered we want to check the spatial diversity performances with regard the antennas configuration between the transmitter and the receiver. Although we can make the situation worst for MIMO spatial diversity. By increasing the path delay integer vector elements to any range we wish, for example, [0 3 4 9 12 15]. But for any range we must choose the same length for the average path gain. And for that I keep it consistent through the simulation scenarios, adding to that, in real world scenario when Rayleigh Fading occur we will change the antennas configuration as we cannot do anything to change this random nature of different path delays.

The other parameter that we did not change is the SNR. And the reason for that is, I did not want show that I am biased to one technology over the other. Where a very slight change in the SNR the results will be perfect (but, of course, the Data Rate still much less than that of spatial multiplexing) and the BER will be ideal. Figure (42) shows the constellation diagram of spatial diversity after the combiner for a (4×4) configuration with SNR equal to 30dB. And the result for the BER is ($6.6e^{-6}$).

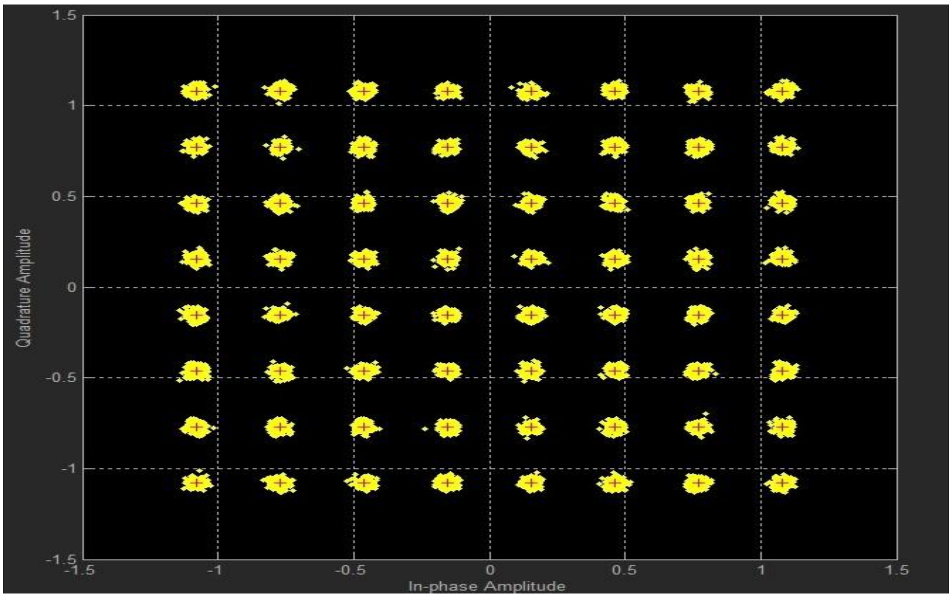


Figure 42: High SNR Spatial Diversity

Figure (42) obtained with a very high SNR and as we mentioned earlier SNR is related to the radio system design and this mean investing more money to obtain such network quality which increase both the capital and the operation expenditure respectively. Last parameter is the Antenna correlation. Although this topic by itself need a lot of investigation as it is related to the relation between diverse antennae. But I could not do it because of the massive information related to antenna correlation. So I leave it with Low correlation that is mean the
Diverse antennae are well spaced, and they transmit on different polarization.

Finally, this topic needs more investigation. For example, I did not cover the different types of Space Frequency Block Coding (SFBC). Which is the key factor of MIMO spatial diversity operation. Where the MIMO spatial Diversity encode the original message into multiple copies then send them over the MIMO diverse antenna. Also, another important factor that is related to the performance of both MIMO systems is the Time Delay calculations associated with transmitting and receiving over MIMO channel. Especially the transient time for calculating the Rank Index of the transmitted signal over a spatial multiplexing MIMO channel (Section 3.2.3). Where it is critical to understand how long it takes to calculate the pilot signal to get the channel estimation and send the Rank Index back to the sender (eNB).
However, the provided information about MIMO channels are all valuable, and it is from legitimate resources and authentic standards, the model that I use to simulate both MIMO schemes are genuine and tested from a very high professional teams from Mathwork. The results are all correct and meet my expectation of the system behaviour for the given parameters.

Chapter Six (Conclusion).

From the results obtained and discussed in Chapter (4) for MIMO spatial multiplexing and MIMO spatial diversity we can conclude the following:

1. MIMO spatial multiplexing can provide high data rates that fulfils user demand for high capacity data transmission. To achieve that MIMO spatial multiplexing splits the input data into a variable number of data streams. The number of these data streams depend on the current configured number of transmit antennas in the system (eNB). However, the number of transmitted antennas depends on the feedback signal from the receiver (UE) (Section 3.2.3, Equation 3.4) this message (Rank Index) used to determine the number of transmit and received antennas. This process is demanding a very sophisticated mathematical algorithms for OFDM signal generating, MIMO channel estimator and turbo coding, which add more complexity to the system and increase the delay associated with this process. MIMO spatial multiplexing is very sensitive to the SNR level, and we can see from scenario three (Section 4.2.3, Table 12) how the BER increased with decreasing the SNR, which lead to decrease the throughput even with high data rates. Spatial multiplexing requires a high SNR level. And to maintain such a high SNR we need a rigid radio network plan (Section 1.2, Figure 1) to provide the desired SNR. However, rigid system design will lead to increase the capital expenditure as we may need to increase the number of eNB in the network. And that needs to assign more resources for these network elements (eNB).
2. MIMO spatial diversity can provide high channel gain this is mean it is concerning about providing better signal quality, by sending multi copies of the data through the diver's transmit antenna, unlike spatial multiplexing the data rate is much less than that provided by spatial multiplexing. There is no correlation between the number of transmit antenna and the number of received antennas. We may transmit on two diverse antenna and receive the data through either one; two or four received antennas. And this is obvious as we send only copies of the original data, not different data streams like spatial multiplexing, and also to get advantages of diversity gain at the receiver. MIMO spatial diversity had low complexity circuit components comparing to that of spatial Multiplexing. In spatial multiplexing, the connection between the transmitter and receiver is considered to be close loop. And that because of the feedback signal from the receiver back to the transmitter.

3. As we previously mentioned for several times, both MIMO technique needs pre-defined SNR level, we can achieve that from radio network planning. Dimensioning of the system parameters, capacity, coverage area, number of cells per cluster, frequency allocation, antenna configuration and transmission capacity (Microwave and Fibre optic) had an immense impact on the MIMO performance. The performance of Self-Optimizing network also affected if had poor network design.

4. Referring to the above information, we can develop an LTE access network based on MIMO spatial multiplexing and MIMO spatial diversity both combined on one radio cell (eNB). Depending on the population density and statistics collected for the nominated coverage area the system designer can implement a cluster of N number of cells. The cells are configured as an MIMO spatial diversity for (n) transmit antennas that are well spaced (≈10λ) with different polarization for obtain low correlation between the antennas. The cell itself (eNB) must have all the major components of spatial multiplexing and spatial diversity circuitry. The design must take in consideration the range of {SNR level, BER, Throughput} that MIMO spatial multiplexing operated over for maximum performance. These ranges of performance parameters considered as a Threshold that is whenever exceeded, the system will switches to MIMO spatial diversity. Last important issue we must address it here is the transmitter power. Where it is running in conjunction with the SNR level. The transmitted power varies depend on the design and communication regulations, so we will insert it with our performance parameters, where any change to the transmitted power will eventually lead to change the SNR level.

6.1 MIMO Self-Optimizing Algorithm (Spatial Multiplexing).

From above mentioned information in point (4) we can use our obtained results from Chapter 4 scenarios to build an algorithm that shows the process of switching between the two MIMO types and I will call this process (MIMO Self-Optimizing Algorithm).

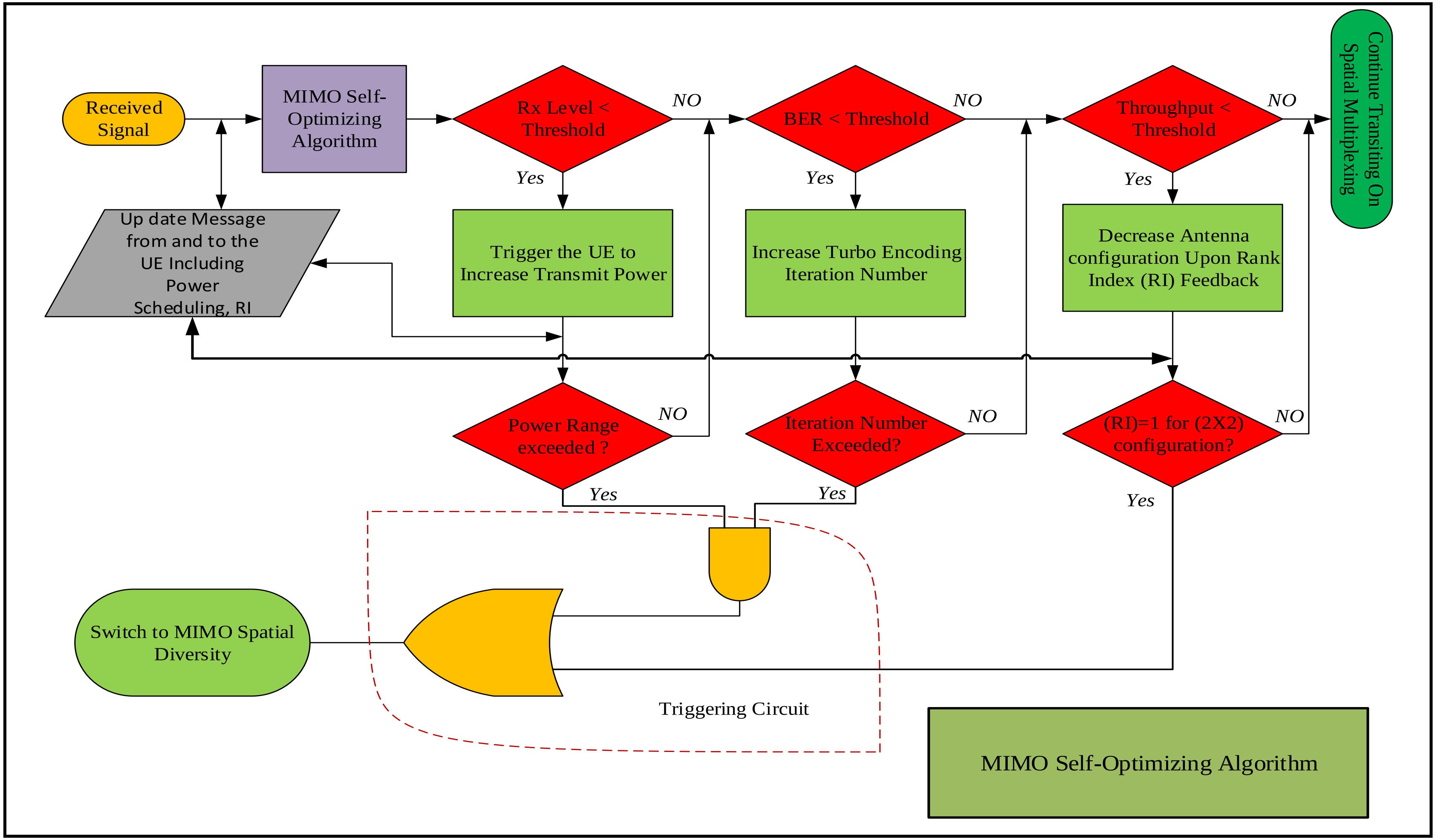


Figure 43: MIMO Self-Optimizing Algorithm (Spatial Multiplexing to Spatial Diversity)

Figure (43) represent the MIMO Self-Optimizing Algorithm where in this algorithm we assumed that the running MIMO configuration is spatial multiplexing. When the (eNB) received the PUSCH (Physical Uplink Shared Channel) first, it would monitor the received signal level as any receiver do by examining the Channel Quality Information (CQI). From the UE back to the (eNB). Then it will compare it with the configured received signal threshold. If the received signal is below the threshold then, it will send a trigger signal through the power management field back to the UE to increase the transmit power. Next it will examine the BER for the whole received PUSCH. If the BER is less that the threshold it will increase the Turbo decoder iterations number as it is the central part of the LTE system to control the error rates. But under the condition that we must not exceed the maximum number of iterations. Finally, the (eNB) examine the throughput of the Uplink rate. This time the (eNB) must check the rank index (RI) associated with the antenna configuration? For example, if the antenna configuration was (4×4) and the rank index received from the UE is equal to one (RI=1) then this is mean there are correlation between the received signals (interferences) which indicate that at least two transmitter antenna at the (eNB) had a strong correlation. In this case the (eNB) reduces the transmit antenna numbers from (4×4) to (2×2) so we get low correlations. If all the parameters criteria are exceeded, then the algorithm switch's to spatial diversity configuration. Here I gave a high priority to the rank index process more than the decoding iteration and power scheduling. However, by increasing the number of iteration we will increase the amount of delay associated with this process. And for power management (increasing Tx Power), most of the time when we increased the power the inter-symbol-interference (ISI) increased too. For these reasons, I implement a simple triggering circuit where it Andding the output of the conditional statement of the power range and the iteration number. Then the output feeds it to one OR gate input and the other OR gate input comes from the rank index conditional statement. In this case if we had (2×2) configuration and we received (RI=1) then the system automatically convert to spatial diversity even if the number of iteration and power range are not exceeded, then to ensure that the algorithm will turn's to spatial diversity I put this OR get to guarantee the process. The second part of this algorithm which is concerning of switching from spatial diversity back to spatial multiplexing shown in Figure (44).

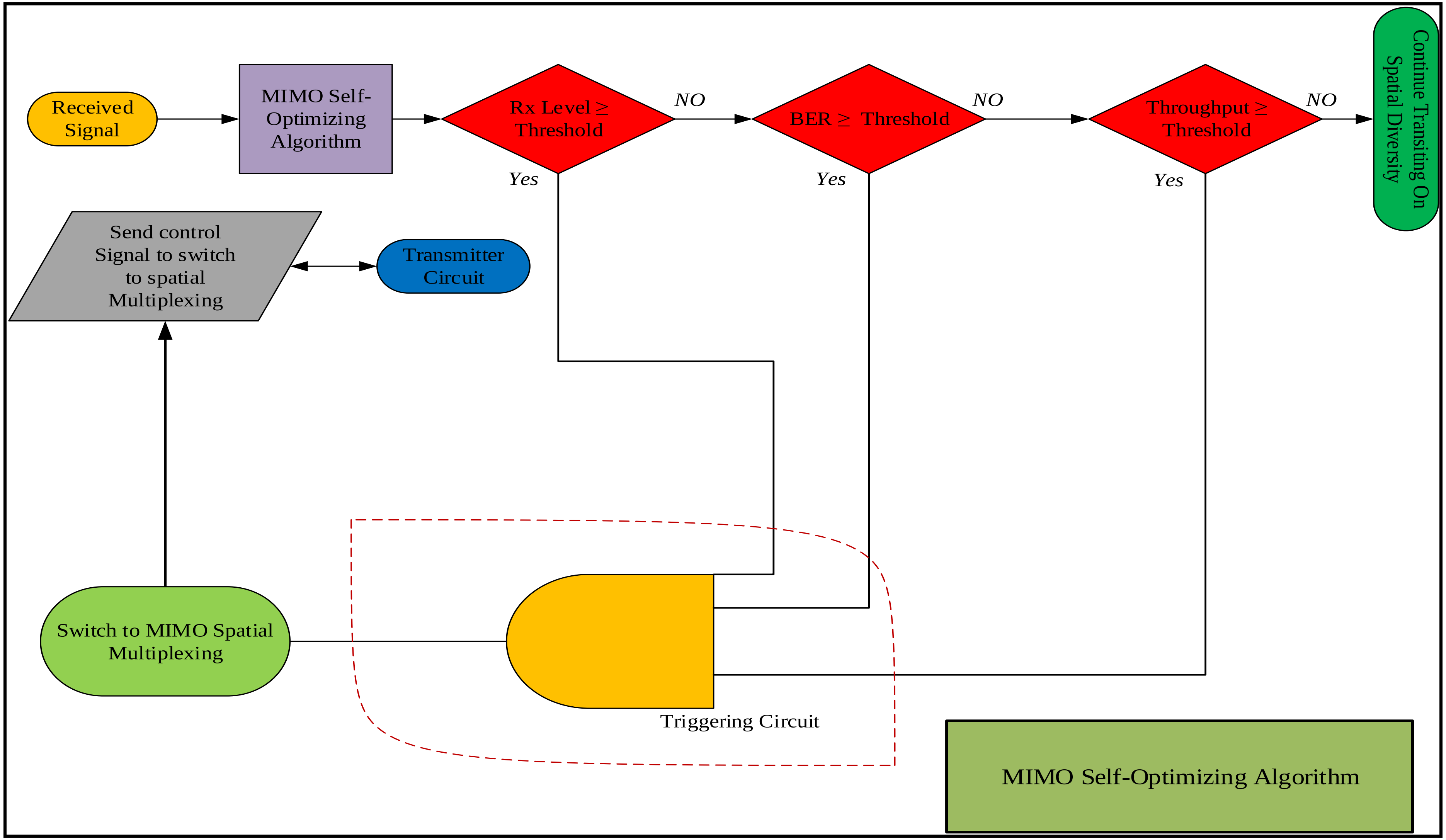


Figure 44: MIMO Self-Optimizing Algorithm (Spatial Diversity to Spatial Multiplexing)

6.2 MIMO Self-Optimizing Algorithm (Spatial Diversity).

The algorithm shown in Figure (44) represent the switching from spatial diversity to spatial multiplexing, I tried here to make the process much faster to guarantee high switching performance for better data rate. As soon the parameters were supporting spatial multiplexing are met the algorithm turns to spatial multiplexing. In the same time, I reduced the triggering circuit to one And gate to insure that all parameters are fulfilled before switching to spatial multiplexing.

6.3 Recommendations and Further work.

I would like to recommend the following:

1. Investigating the correlation between the antennas in both spatial multiplexing and spatial diversity, where we could build an algorithm to readjust the antennas polarizations (different angels of polarizations) between transmit and receive antennas, also readjusting the spacing between the antennas in the transmit side only. Al these readjusting can be done automatically without human intervening, which reduces the operation cost for optimization.

2. Following the same issues in point one, also we can build an algorithm to readjust the antennas height and tilt (mechanically and electrically), to get better performance signal propagation.

3. For achieving better results and more in-depth understanding, I recommend using SDR (Software Defined Radio) in conjunction with MATLAB communication tool box to simulate the effect of changing the mentioned parameters in point one and two.

4. I recommend that the university open channels for postgraduate students with telecommunication industry. Especially with 4G operators. By involving with their development department and get more understanding of the system operation. For example the students can get the KPI (Key Performance Index) which is a statistical information collected by the network server about different kind of parameters and faults occurred during the operation. This will increase the technical content of the research and improve the quality of the research.

5. Using more powerful software that can simulate the overall performance of the targeted objects, for example in my project we may use this kind of software to see the impact of self-optimizing on Handover processing, delay performances, capacity per user… etc.

Appendix A

A.1 IEEE 802.16d Path-Loss Model.

This code is for Figure (6) of Chapter 2 Section 2.1.1, according to (Cho, et al, 2010) this code is representing the IEEE 802.16d Path-Loss Model, I just modified the frequency range.

```
% plot_PL_IEEE80216d.m

clear, clf, clc
fc= 2.6e9; htx=[40 40]; hrx=[2 10]; distance=[1:1000];
for k=1:2
    y_MIEEE16d(k,:)=PL_IEEE80216d(fc,distance,'A',htx(k),hrx(k), 'okumura',
'mod');
end
plot(122), semilogx(distance,y_MIEEE16d(1,:),'k:','linewidth',1.5)
hold on, semilogx(distance,y_MIEEE16d(2,:),'k-','linewidth',1.5)
grid on, axis([1 1000 10 150])
title(['IEEE802.16d Path-loss Model,f_c=',num2str(fc/1e6),'MHz'])
xlabel('Distance[m]'), ylabel('Pathloss[dB]')
legend('h_{Tx}=30m, h_{Rx}=2m','h_{Tx}=30m, h_{Rx}=10m',2)
```

A.2 Rayleigh and Rician Fading Distribution.

This code is for Figure (7) of Chapter 2 Section 2.1.2, according to (Cho, et al, 2010) the code representing the Rayleigh and Rician fading distribution.

```
function H=Ray_model(L)
% Rayleigh channel model
% Input : L = Number of channel realizations
% Output: H = Channel vector
H = (randn(1,L)+j*randn(1,L))/sqrt(2);
function H=Ric_model(K_dB,L)
% Rician channel model
% Input : K_dB = K factor[dB]
% Output: H = Channel vector
K = 10^(K_dB/10);
H = sqrt(K/(K+1)) + sqrt(1/(K+1))*Ray_model(L);
 % plot_Ray_Ric_channel.m
clear, clf
N=200000; level=30; K_dB=[-35 20];
gss=['k-s'; 'b-o'; 'r-^'];
% Rayleigh model
Rayleigh_ch=Ray_model(N);
[temp,x]=hist(abs(Rayleigh_ch(1,:)),level);
plot(x,temp,gss(1,:)), hold on
% Rician model
for i=1:length(K_dB);
    Rician_ch(i,:) = Ric_model(K_dB(i),N);
    [temp x] = hist(abs(Rician_ch(i,:)),level);
    plot(x,temp,gss(i+1,:)) end
    xlabel('x Random variables'), ylabel('Occurrence')
    legend('Rayleigh','Rician, K=-35dB','Rician, K=20dB')
```

A.3 Orthogonality.

This code is for Figure (9) of Chapter 2 Section 2.2, according to (Cho, et al, 2010), this code is representing the orthogonality of different sinusoid signals.

```
% test_orthogonality.m
% To check the orthogonality among some sinusoidal signals
% with different frequencies/phases

clear, clf
T=1.6; ND=1000; nn=0:ND; ts=0.002; tt=nn*ts; % Time interval
Ts = 0.1; M = round(Ts/ts); % Sampling period in continuous/discrete-time
nns = [1:M:ND+1]; tts = (nns-1)*ts; % Sampling indices and times
ks = [1:4 3.9 4]; tds = [0 0 0.1 0.1 0 0.15]; % Frequencies and delays
K = length(ks);
for i=1:K
    k=ks(i); td=tds(i); x(i,:) = exp(j*2*pi*k*(tt-td)/T);
    if i==K, x(K,:) = [x(K,[302:end]) x(K-3,[1:301])]; end
    subplot(K,2,2*i-1), plot(tt,real(x(i,:))),
    hold on, plot(tt([1 end]),[0 0],'k'), stem(tts,real(x(i,nns)),'.')
end
N = round(T/Ts); xn = x(:,nns(1:N));
xn*xn'/N % check orthogonality
Xk = fft(xn.').'; kk = 0:N-1;
for i=1:K,
    k=ks(i); td=tds(i); subplot(K,2,2*i), stem(kk,abs(Xk(i,:)),'.');
end
```

Appendix B

In this Appendix I will provide the simulation model code for LTE PDSCH Spatial Diversity, as regard the spatial Multiplexing model I will provided with a CD room as it is a Simulink model with embedded MATLAB functions, also I will copy all the codes previous codes including this one too on the CD. According to Mathworks team the code is as follow:

```
 function pber = LTETransmitDiversitySim(chanBW, contReg, numTx, numRx, ...
    modType, chanMdl, maxDopp, pathDelays, pathGains, corrLvl, snrdB, ...
    chanEst, numSFrames, showScopes, showSpectrum)
%LTETRANSMITDIVERSITYSIM LTE Transmit Diversity simulator.
%   LTE Transmit Diversity defined for 2 and 4 Tx antennas.
%   Single codeword transmission for FDD mode, PDSCH processing only.
%   Assumes channel is constant for 2 sub-carriers.
%
%   PBER = LTETransmitDiversitySim(chanBW, contReg, numTx, numRx, modType,
...
%    chanMdl, maxDopp, pathDelays, pathGains, corrLvl, snrdB, chanEst,...
%    numSFrames, showScopes, showSpectrum)
%   where
%    chanBW       - {1,2,3,4,5,6} maps to [1.4, 3, 5, 10, 15, 20] MHz
%    contReg      - {1,2,3} for >=10MHz, {2,3,4} for <10Mhz
%    numTx        - {2, 4}
%    numRx        - {1, 2, 4}
%    modType      - [1,2,3] maps to ['QPSK','16QAM','64QAM']
%    chanMdl      - one of {'Frequency-flat static', 'User-defined'}
%    maxDopp      - scalar
%    pathDelays   - integer vector of multiples of channel input sample
time
%    pathGains    - vector, same length as pathDelays
%    corrLvl      - one of {'Low', 'Medium', 'High'}
%    snrdB        - scalar
%    chanEst      - 1 for channel estimation, 0 for ideal estimates
%    numSFrames   - scalar, length of simulation
%    showScopes   - 1 to enable, 0 to disable
%    showSpectrum - 1 to enable, 0 to disable
%
%   The function uses persistent objects to help speed up the simulations.
%   Multiple runs with different parameter values may require a CLEAR
%   ALL to reinstantiate these objects.
%
%   Example: 10MHz, 16QAM, 2x1 link simulation with user-defined channel
%     clear all;    % clear any prior objects
%     PBER = LTETransmitDiversitySim(4, 2, 2, 1, 2, 'User-defined',...
%               5, [0 5 8], [0 -3 -6], 'Low', 12, 0, 30, 0, 0)
%
%   See also LTEDownlinkSim.

%   Copyright 2012-2013 The MathWorks, Inc.
```

```
disp('Simulating LTE Downlink PDSCH with Transmit Diversity')
%% Create the prm structures

% PDSCH and channel parameters

[prmLTEPDSCH, prmMdl] = ltePDSCHprms(2, chanBW, contReg, modType, ...
                                     chanMdl, numTx, numRx);
prmMdl.maxDopp = maxDopp;
prmMdl.pathGains = pathGains;
prmMdl.pathDelays = pathDelays;
prmMdl.corrLevel = corrLvl;
prmMdl.showScopes = showScopes;

%% Object constructions

disp('    Creating objects for simulation.');
switch modType

    case 1
        symMap = [0 2 3 1];
        hMod = comm.PSKModulator('ModulationOrder', 4, 'BitInput', true,
...
            'PhaseOffset', pi/4, 'SymbolMapping', 'Custom', ...
            'CustomSymbolMapping', symMap);

        hDemod = comm.PSKDemodulator('ModulationOrder', 4,...
            'BitOutput', true, 'PhaseOffset', pi/4, ...
            'SymbolMapping', 'Custom', 'CustomSymbolMapping', symMap, ...
            'DecisionMethod', 'Approximate log-likelihood ratio', ...
            'VarianceSource', 'Input port');
    case 2

        symMap = [11 10 14 15 9 8 12 13 1 0 4 5 3 2 6 7];
        hMod = comm.RectangularQAMModulator('BitInput', true, ...
            'NormalizationMethod', 'Average power',...
            'SymbolMapping', 'Custom', 'CustomSymbolMapping', symMap);

        hDemod = comm.RectangularQAMDemodulator('BitOutput', true, ...
            'NormalizationMethod', 'Average power',...
            'SymbolMapping', 'Custom', 'CustomSymbolMapping', symMap,...
            'DecisionMethod', 'Approximate log-likelihood ratio', ...
            'VarianceSource', 'Input port');
    case 3

        symMap = [47 46 42 43 59 58 62 63 45 44 40 41 57 56 60 61 37 ...
                  36 32 33 49 48 52 53 39 38 34 35 51 50 54 55 7 6 2 ...
                  3 19 18 22 23 5 4 0 1 17 16 20 21 13 12 8 9 25 24 28 ...
                  29 15 14 10 11 27 26 30 31];
```

```
hMod = comm.RectangularQAMModulator('ModulationOrder', 64, ...
            'BitInput', true, 'NormalizationMethod', 'Average power', ...
            'SymbolMapping', 'Custom', 'CustomSymbolMapping', symMap);

        hDemod = comm.RectangularQAMDemodulator('ModulationOrder', 64, ...
            'BitOutput', true, 'NormalizationMethod', 'Average power', ...
            'SymbolMapping', 'Custom', 'CustomSymbolMapping', symMap,...
            'DecisionMethod', 'Approximate log-likelihood ratio', ...
            'VarianceSource', 'Input port');
end

% MIMO channel
if ( strcmp(chanMdl, 'Frequency-flat static') )
    chanObj = comm.MIMOChannel('SampleRate', prmLTEPDSCH.chanSRate, ...
        'MaximumDopplerShift', 0, ...
        'PathDelays', 0,...
        'AveragePathGains', 0,...
        'RandomStream', 'mt19937ar with seed',...
        'Seed', 100,...
        'SpatialCorrelation', false,...
        'NumTransmitAntennas', numTx,...
        'NumReceiveAntennas', numRx,...
        'PathGainsOutputPort', true);
elseif strcmp(chanMdl, 'User-defined')

    switch prmMdl.corrLevel
        case 'Low'
            txCorrelationCoeff = 0;
            rxCorrelationCoeff = 0;
        case 'Medium'
            txCorrelationCoeff = 0.3;
            rxCorrelationCoeff = 0.9;
        case 'High'
            txCorrelationCoeff = 0.9;
            rxCorrelationCoeff = 0.9;
    end
    Rt = getCorrelationMatrix(numTx, txCorrelationCoeff);
Rr = getCorrelationMatrix(numRx, rxCorrelationCoeff);

    chanObj = comm.MIMOChannel('SampleRate', prmLTEPDSCH.chanSRate, ...
        'MaximumDopplerShift', prmMdl.maxDopp, ...
        'PathDelays', prmMdl.pathDelays*(1/prmLTEPDSCH.chanSRate),...
        'AveragePathGains', prmMdl.pathGains,...
        'RandomStream', 'mt19937ar with seed',...
        'Seed', 100,...
        'TransmitCorrelationMatrix', Rt,...
        'ReceiveCorrelationMatrix', Rr,...
        'PathGainsOutputPort', true);
end
```

```
% AWGN channel
nVar = 10.^(0.1.*(-snrdB)); % assume unit sigPower
hAWGN = comm.AWGNChannel('NoiseMethod', 'Signal to noise ratio (SNR)',...
    'SNR', snrdB, 'RandomStream', 'mt19937ar with seed', 'Seed', 67);

% Error meter
hPBer = comm.ErrorRate;

% Constellation Scopes
if showScopes
    persistent hScope1_1 hScope2; %#ok, need to retain figures after run
    constell = constellation(hMod);
    hScope1_1 = comm.ConstellationDiagram('ReferenceConstellation',
constell,...
        'YLimits', [-2 2], 'XLimits', [-2 2], 'Position',...
        figposition([5 50 20 25]), 'Name', 'Post OFDM Rx - 1st Rx');
    if (prmLTEPDSCH.numRx>1)
        persistent hScope1_2; %#ok
        hScope1_2 = comm.ConstellationDiagram('ReferenceConstellation',
constell,...
            'YLimits', [-2 2], 'XLimits', [-2 2], 'Position', ...
            figposition([5 15 20 25]), 'Name', 'Post OFDM Rx - 2nd Rx');end
    if (prmLTEPDSCH.numRx>2)
        persistent hScope1_3; %#ok
        hScope1_3 = comm.ConstellationDiagram('ReferenceConstellation',
constell,...
            'YLimits', [-2 2], 'XLimits', [-2 2], 'Position', ...
            figposition([26 50 20 25]), 'Name', 'Post OFDM Rx - 3rd Rx');
end
    if (prmLTEPDSCH.numRx>3)
        persistent hScope1_4; %#ok
        hScope1_4 = comm.ConstellationDiagram('ReferenceConstellation',
constell,...
            'YLimits', [-2 2], 'XLimits', [-2 2], 'Position', ...
            figposition([26 15 20 25]), 'Name', 'Post OFDM Rx - 4th Rx');
    end
hScope2 = comm.ConstellationDiagram('ReferenceConstellation', constell,...
        'YLimits', [-1.5 1.5], 'XLimits', [-1.5 1.5], 'Position', ...
        figposition([50 32 20 25]), 'Name', 'Post MIMO Rx - combined
stream');end

% Spectrum Scope
if showSpectrum
    persistent hSpecAnal; %#ok, need to retain figures after run
    hSpecAnal = dsp.SpectrumAnalyzer('SampleRate', prmLTEPDSCH.chanSRate,
...
        'SpectrumType', 'Power density', 'PowerUnits', 'dBW', ...
        'RBWSource', 'Property',   'RBW', 15e3, ...
        'FrequencySpan', 'Span and center frequency', ...
        'Span', prmLTEPDSCH.BW, 'CenterFrequency', 0, ...
        'Window', 'Rectangular', 'SpectralAverages', 10, ...
        'YLimits', [-115 -45], 'YLabel', 'PSD', ...
        'Title', 'Transmitted & Received Signal Spectrum', ...
        'ShowLegend', true);
    hSpecAnal.getFramework.Visual.Plotter.UserDefinedChannelNames = ...
            {'Transmitted', 'Received'};end
```

```
%% LTE PDSCH processing
nS = 0; % Slot number, one of [0:2:18]

if chanEst
    disp('        MIMO channel estimation will be used.')
else
    disp('        Ideal channel gains will be used.')
end

%% Simulation loop
for idx = 1:numSFrames  % subframe processing
    disp(['    Processing #' num2str(idx) ' subframe.']);

    numTx = prmLTEPDSCH.numTx;

    %% Generate codeword
    data = lteGenPayload(nS, 0, prmLTEPDSCH.numPDSCHBits); % seed = 0

    %% Transmitter
    % Scramble codeword (=0)
    scramOut = lteScramble(data, nS, 0, prmLTEPDSCH.maxG);

    % Modulate
    modOut = step(hMod, scramOut);

    % Map codeword to layers
    % and Transmit Diversity encoding
    preOut = lteTDEncode(modOut, numTx);

    % Generate Cell-Specific Reference (CSR) signals
    csr = lteCSRGen(nS, numTx);

    % Resource grid filling
    txGrid = lteREMapper(preOut, csr, nS, prmLTEPDSCH);

    % OFDM transmitter
    txSig = lteOFDMTx(txGrid, prmLTEPDSCH.Nrb);

    %% Channel
    % MIMO Fading channel
    [rxFade, chPathG] = step(chanObj, txSig);

    % Add AWG noise
    rxSig = step(hAWGN, rxFade);

    % Update Spectrum scope
    if (showSpectrum)
       % Take last OFDM symbol of the subframe, for the first antenna.
        %        - no overhead, CSR, or nulls are present.
        step(hSpecAnal, [txSig(end-prmLTEPDSCH.N+1:end, 1) ...
                         rxSig(end-prmLTEPDSCH.N+1:end, 1)]);
    end
```

```
%% Receiver
    % OFDM Rx
    rxGrid = lteOFDMRx(rxSig, prmLTEPDSCH.Nrb, prmLTEPDSCH.Nrb_sc,...
                       prmLTEPDSCH.Ndl_symb);

    % Extract data and pilot signals
    [dataRx, csrRx] = lteExtData(rxGrid, nS, prmLTEPDSCH);

    % Plot received data - dataRx
    if showScopes && (nS~=0 && nS~=10)
        step(hScope1_1, dataRx(:, 1));
        if (prmLTEPDSCH.numRx>1)
            step(hScope1_2, dataRx(:, 2));
        end
        if (prmLTEPDSCH.numRx>2)
            step(hScope1_3, dataRx(:, 3));
        end
        if (prmLTEPDSCH.numRx>3)
            step(hScope1_4, dataRx(:, 4));
        end
    end

    % MIMO channel estimation
    if chanEst % estimate channel
        chEst = lteChanEstimate(prmLTEPDSCH, csrRx, csr);
        hD = lteExtractHData(chEst, nS, prmLTEPDSCH);
    else % use ideal channel - from MIMO object
        hD = lteIdChEst(prmLTEPDSCH, prmMdl, chPathG, nS);
    end

    % Transmit diversity combining - SFBC & SFBC with FSTD
    yRec = lteTDCombine(dataRx, hD, numTx, prmLTEPDSCH.numRx);

    % Plot received MIMO combined data - yRec
    if showScopes && (nS~=0 && nS~=10)
        step(hScope2, yRec(:, 1));
    end

    % Demodulate
    demodOut = step(hDemod, yRec, nVar);

    % Descramble both received codewords
    rxCW = lteDescramble(demodOut, nS, 0, prmLTEPDSCH.maxG);
```

```
%% Analysis
    % Calculate PDSCH bit errors
    pber = step(hPBer, data, logical((1-sign(rxCW))./2));

    % Manage slot number with each subframe processed
    nS = nS + 2;
    if nS > 19
        nS = mod(nS, 20);
    end
end

end

%------------------------------------------------------------------------------
function R = getCorrelationMatrix(NumAntennas, r)
    switch NumAntennas
        case 1
            R = 1;
        case 2
            R = [1 r; r 1];
        case 4
            R = [1          r^(1/9)     r^(4/9)     r;          ...
                 (r^(1/9))  1           r^(1/9)     r^(4/9);  ...
                 (r^(4/9))  (r^(1/9))   1           r^(1/9);  ...
                 r          (r^(4/9))   (r^(1/9))   1];
    end
end

% [EOF]
```

References

ITU-R M.1225. (1997). *GUIDELINES FOR EVALUATION OF RADIO TRANSMISSION TECHNOLOGIES FOR IMT-2000.* Retrieved from RECOMMENDATION ITU-R M.1225.itu.int: https://www.itu.int/dms_pubrec/itu-r/rec/m/R-REC-M.1225-0-199702-I!!PDF-E.pdf

3GPP TR 25.892 . (2004). *Technical Specification Group Radio Access Network;Feasibility Study for OFDM for UTRAN enhancement;(Release 6).* Valbonne: 3GPP Organization.

3GPP,Rel.10. (2013, September). *3GPP Specification detail.* Retrieved from 3GPP.org: http://www.3gpp.org/DynaReport/36300.htm

A.B.Gershman, N.D.Sidiropoulos. (2005). *Space-Time Processing for MIMO communication.* Sussex: John Wiley & Sons.

Alcatel-Lucent. (2012). 9400 LTE RAN TLA3.0-LA4.0 Technical Overview. France.

Alexander, M. R. (2013, June). Autonomous Self-Optimization of Coverage and Capacity in LTE cellular Networks. *IEEE Transactions On Vehicular Technology*, pp. Vol.62, NO.5.

Angel Lozano, Nihar Jindal. (2010). Transmit Diversity vs. Spatial Multiplexing in Modern MIMO Systems . *IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS*, VOL. 9, NO. 1.

B.P.Lathi. (2005). *Linear System and Signals.* NewYork: Oxford University Press.

Bingham, J. A. (1990). Multicarrier Modulation for Data Transmission: An Idea Whose Time Has Come . *IEEE Communication Magazine*.

Cho, et al. (2010). *MIMO-OFDM Wireless Communications With MATLAB.* Repablic Of Korea: Johan Wiley & Sons.

CLARKE, R. H. (1968). A Statistical Theory of Mobile-Radio reception. *THE BELL SYSTEM TECHNICAL JOURNAL*.

Claude Berrou, A. G. (1993). *France Patent No. 9105279 (France), 92460011.7(Europe).*

Claude Oestges, Brun Clerckx. (2007). *MIMO Wireless Communication: From Real-World Propagation to Space-Time Code Design.* SanDiego: Academic Press Elsevier.

D.C.Cox, et al. (1983). Measurments of 800-MHz Radio Transmission Into Buildings With Metallic Walls. *THE BELL SYSTEM TECHNICAL JOURNAL*, Vol.62, NO.9.

Daniel W. Bliss, et al. (2005). MIMO Wireless Communication. *LINCOLN LABORATORY JOURNAL* , VOLUME 15, NUMBER 1.

Don. (2011, September 20). *Expert Opinion* . Retrieved from LTE Universty: http://lteuniversity.com/get_trained/expert_opinion1/b/donhanley/archive/2011/09/20/codewords-and-layers-and-ports-oh-my.aspx

Erik Dahlman, Stefan Parkvall, Johan Sköld. (2014). *4G:LTE/LTE-Advanced for Mobile Broadband.* Waltham: Elsevier.

Frame Structure - Downlink . (n.d.). Retrieved from ShareTechNote: http://www.sharetechnote.com/html/FrameStructure_DL.html

G.J. FOSCHINI, M.J. GANS. (1998). On Limits of Wireless Communications in a Fading Environment when Using Multiple Antennas. *Wireless Personal Communications 6*, 311–335.

Hourani, H. (2004/2005). *An Overview of Diversity Techniques in Wireless Communication Systems.* Helsinki: Helsinki University of Technology, S-72.333 Postgraduate Course in Radio Communications .

Huawei Technologies Co., L. (2010, May 31). LTE Radio Network Planning Introduction. China .

IEEE, 802-16j. (2007-02-19, January 19). *Multi-hop Relay System Evaluation Methodology (Channel Model and Performance Metric).* Retrieved from http://ieee802.org/: http://ieee802.org/16/relay/docs/80216j-06_013r3.pdf

ITU-R. (1997). *Principles and Approaches on Evolution to IMT-2000/FPLMTS Handbook on Land Mobile (Including Wireless Access) Volume 2.* Geneva: International Telecommunication Union (ITU).

Jargen Bach Andersen, Theodore S. Rappaport, and Susumu Yoshida. (1995). Propagation Measurements and Model for Wireless Communications Channels. *IEEE Communications Magazin*.

Leo Montreuil, Rich Prodan, Tom Kolze. (2013, January). *OFDM TX Symbol Shaping 802.3bn.* Retrieved from ieee802.org: http://www.ieee802.org/3/bn/public/jan13/montreuil_01a_0113.pdf

Mathworks. (2013). *Documentation Center.* Retrieved from mathworks.co.uk: http://www.mathworks.co.uk/help/comm/ref/turboencoder.html

Mathworks, D. (2014). MATLAB help. Mathwork .

Ove Edfors, et al. (1996). *An introduction to Orthogonal Frequency-division.* Lulea: Lulea University of technology.

Rappaport, T. S. (2002). *Wireless communication: Principles & Practice 2/E.* New Jersey: Prentice Hall.

S. Benedetto,D. Divsalar, G. Montorsi, F. Pollarab. (1996). *A Soft-Input Soft-Output Maximum A Posteriori (MAP) Module to Decode Parallel and Serial Concatenated Codes.* Torino: Jet Propulsion Lab TDA Progress Report.

S.D.Ma, T.I.Yuk. (n.d.). *Convolutional Codes.* Retrieved from eee.hku.hk: http://www.eee.hku.hk/~sdma/elec7073/Part2-3-Convolutional%20codes.pdf

Sklar, B. (2013). *Digital communications Fundimintal and Applications .* Person.

Volakis, J. L. (2007). *Antenna Engineering Handbook.* NewYork: McGraw-Hill.

Wong, K. (2012). *Funamentals of Wireless Communication Engineering Technologies.* New Jersey: Johan Wiley & Sons.

Zarrinkoub, H. (2012, March 28). *Videos and Webinars*. Retrieved from Mathworks.www.mathworks.co.uk: http://www.mathworks.co.uk/videos/modeling-a-4g-lte-system-in-matlab-92983.html