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Evaluation of the Impact of Higher Order Modulation and MIMO for LTE Downlink

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Abstract: Long Term Evolution (LTE) represents the standardization efforts by 3GPP for developing a new high data rate radio access technique for the mobile cellular communication systems. Long Term Evolution provides a smooth evolutionary for the existing 2nd and 3rd generation (2G and 3G) systems and is the next step towards the next generation known as 4th Generation (4G) of the cellular systems. With the improved spectrum efficiency, simplified architecture and the ability to reuse low frequency spectrum and the innovative radio interface, LTE is an evolution from the current packet and circuit switched networks to a simple all IP environments. The LTE physical layer provides an extremely efficient way of transporting both control information signaling and the data between eNodeB (enhanced base station) and the UE (mobile user equipment). The physical layer of LTE utilizes some new and much advanced techniques including OFDM (Orthogonal Frequency Division Multiplexing) and MIMO (Multiple Input Multiple Output). The focus of this work is on performance analysis of LTE downlink physical layer, more specifically the impact of higher order modulation and spatial multiplexing with MIMO techniques using a simulation model developed in MATLAB. The results of this study show that the physical layer performance of the LTE downlink can be greatly enhanced in terms of throughput and BER with higher order modulation and MIMO techniques.

Key words: UMTS Evolution, LTE, Physical Layer, OFDM, QAM, MIMO

INTRODUCTION

Long Term Evolution (LTE) has emerged to cater for the insatiable demands for high data rate, low latency services for a very large number of multimedia users that are expected to provide significantly increased revenues to service providers in the coming years. In order to meet the needs of high data rate, low latency transport services, 3GPP has come up with an emerging radio access technique in the form of LTE for cellular mobile communication systems that aim to provide highly optimized data transport capabilities. Whereas the primary focus of the earlier mobile communication systems was on the voice service only, the emphasis has entirely shifted to the development of high capacity data oriented systems. The tendency towards data centric networks started with the third generation (3G) Universal Mobile Telecommunication Systems (UMTS) and is now attaining fulfillment in its descendant, the “LTE (Long Term Evolution)”. LTE is the next step towards the development of the next generation known as 4th Generation (4G) of the cellular system that started with the existing 2G and the 3G networks (Martín-Sacristán *et al.,* 2009).

LTE is being developed with specific objectives of achieving enhanced linking of people by providing increased functions for information transfer to enable multiple diverse forms of communication. LTE is a new standard for mobile radio communications having flat IP-based network with improved data rates, low latency, coverage and mobility (Martín-Sacristán *et al.,* 2009). Long Term Evolution has been designed right from the outset to afford packet-oriented services for all applications including voice and video. The key attraction of LTE for operators is its spectrum flexibility, as it can be deployed in various frequencies bands with minimal changes in radio interface. In parallel to that, it is also backward compatible with non-3GPP networks, for instance WIMAX. For operators, the evolution is cost effective delivery, convergence between fixed and wireless networks (Ergen, 2009).

With the significantly improved spectrum efficiency, simplified architecture and the ability to reuse low frequency spectrum, LTE is expected to boost capacity for both voice and data delivered at a significantly lower cost as compared to the previous technologies like UMTS. The focus of this work is to analyze the

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performance of LTE physical Layer, more specifically the impact of higher order modulation and spatial multiplexing using MIMO techniques. The paper is organized as: Section II presents a brief description of LTE physical layer functions. In Section III, a simulation model of the LTE physical layer with advanced techniques is presented. Section IV provides the simulation results and discussion and Section V concludes the work.

II. 3GPP Long Term Evolution (LTE):

Long Term Evolution (LTE) is expected to enable considerably higher data rates along with much lower packet latency and thus will enable the cellular communication services to meet the need for cellular technology until 2020 and well beyond (Dahlman *et al.,* 2007). LTE is the upgraded version of UMTS cellular Technology. For service providers deploying both the 3GPP and non-3GPP systems, LTE can offer a smooth evolutionary track. With the increased spectrum efficiency, highly simplified architecture and the capability to reuse low frequency spectrum and the innovative radio interface, LTE represents an evolution from the current packet and circuit switched networks to a simple all IP network.

New LTE networks will interconnect seamlessly with the existing 3GPP and non-3GPP (3GGP2) networks by providing the convenience of keeping the existing global roaming agreements and ability to an efficient hand-over to the 2G/3G systems or the sub-layer where LTE coverage is not in existence (Hung *et al.,* 2009). LTE is able to provide much higher data rates than ever before achieved over any the air interface. LTE offers greater wide-area coverage and support for seamless mobility for all the types of application services. LTE also employs advanced spatial technology known as MIMO (Multiple Input Multiple Output) which involves multiple antenna transmission and reception. LTE is characterized by the fact that MIMO combined with QAM higher-order modulation techniques are integral components of the system and are being used first time in cellular mobile networks (Zyren, 2009).

LTE is very versatile technology that will meet the requirements of 3GPP. The typical peak data rates being considered for LTE are 100Mbit/s downlink and 50Mbit/s uplink whereas the Radio Access Network (RAN) latency has been reduced to 10ms. LTE aims to achieve much higher spectrum efficiency (2 to 4 times as compared with UMTS HSPA) and use of scalable bandwidth of 20MHz, 15MHz, 10MHz, 5MHz and <5MHz in both paired and unpaired frequency bands. Further, LTE has been designed to achieve cost-effective migration from Universal Terrestrial Radio Access (UTRA) with optimized radio interface, simpler architecture, enhanced broadcasting, and optimized IP services (i.e. in the packet-switched domain). Further LTE will provide better support for inter-working with existing 3G systems and non-3GPP standards (Dahlman *et al.,* 2007; Zyren, 2009).

The LTE MAC layer uses OFDMA (Orthogonal Frequency Division Multiple Access) on the downlink (DL) whereas for uplink (UL), SC-FDMA (Single Carrier-Frequency Division Multiple Access) is being employed. The physical layer of LTE plays an extremely critical role in achieving the required high capacity and coverage. Therefore, it is the most important factor when performance of LTE system is compared with the other existing systems. The LTE physical layer affords a exceedingly efficient way of transporting both control signaling and the data between eNodeB (Enhanced Base Station) and the UE (mobile User Equipment). The physical layer of LTE includes many novel advanced techniques that have been introduced first time to the cellular or mobile networks (Zyren, 2009; Sesia, 2009).

III. Long term Evolution (LTE) Physical Layer Model:

The primary function of LTE PHY is to bridge the eNodeB and UE. The interface between the PHY and the MAC layer has methods for each of the control signaling and also transmitting and receiving Transport Blocks (TBs). It is also responsible for synchronizing the Transmission Time Interval (TTI) between the eNodeB and the UE (Dahlman *et al.,* 2007). The physical layer of LTE employs some new and much advanced technologies including Multiple Input Multiple Output (MIMO) and Orthogonal Frequency Division Multiplexing (OFDM) for enhanced data transport. The physical layer of LTE focuses on the designing parameters used in system such as bandwidth, data rates, multiplexing schemes, physical-layer hybrid-ARQ processing, modulation schemes, antenna schemes and the coding schemes used (Sesia *et al.,* 2009). The signals generated in physical layer (L-1) are used for the purpose of radio channel estimation, cell identification and system synchronization.

The processing for downlink physical layer of LTE is shown in Figure-1. From physical layer, MAC layer is served via transport channel. Data on transport channel is organized in the form of Transport Block (TB). In each Transmission Time Interval (TTI), at most one transport block is transmitted over radio interface (3GPP TS 36.201, 2009). If spatial multiplexing (MIMO) is used, then more the one transport block can be transmitted, depending on number of transmitting antennas. A brief description of various physical layer functions is as follows:

Channel Coding:

Channel coding is performed in order to protect the data from error. In channel coding n input bits are mapped to k bit. In this way the encoder rate is k/n. According to LTE specification, different channel coding rates can be adopted such as 1/2, 2/3, 3/4 and 4/5. For our model we have selected rate 3/4 Convolutional encoder. If the convolution codes use 2^n symbols then the vector length of input will be L*n. And when the decoded data use 2^k symbols then the length of the output vector will be L*k, where the integer L is the number of frames which are processed in every step. For the sample based input vector, L=1 is used whereas for frame based input vector, L may be any positive integer (3GPP TS 36.212, 2009).

Interleaving:

Interleaving is used to reduce the errors caused by the burst errors in communication system. Burst errors can eliminate a large number of bits in a row and normal error correction schemes that handle uniformly distributed errors, can not work properly. Interleaving helps distribute the impact of burst errors and thus improve the reliability of data transmission. Generally error control bits are sent with information bits that permit to correct the errors at the receiver that occur during the data transmission. If the burst errors occur during the transmission of data, one code word may be severely affected in such a way that code word may not be correctly decoded. To minimize the impact of burst errors, the bits in a certain number of code words are interleaved on the transmitter side. Interleaving is a less complex and cost effective technique to reduce the burst errors. The disadvantage of this interleaving is that it increases the latency. The main purpose of interleaving is to protect data from burst error. Interleaving method used in physical layer model is matrix interleaving. It generates a matrix according to input data frame size, e.g. If input frame size is 100, it will generate a matrix of 10X10 and start filling the data row wise in matrix and then outputs the data by reading column wise (3GPP TS 36.212, 2009).

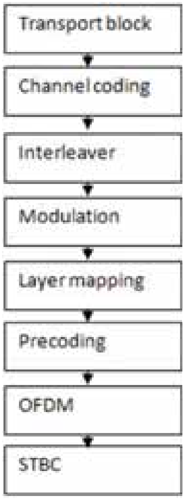

Fig. 1: LTE Downlink physical layer model

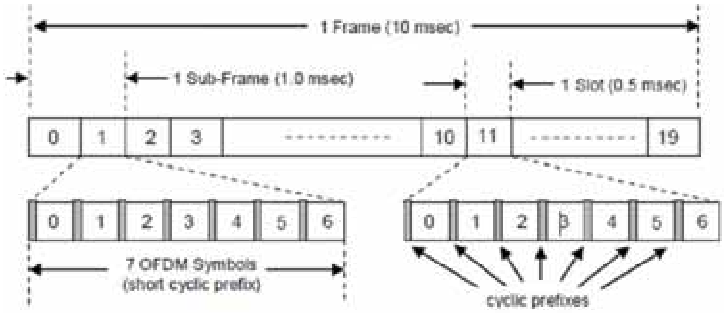

Fig. 2: LTE Generic Frame Structure

LTE Generic Frame Structure:

Both the LTE downlink and uplink share the generic frame structure. Both FDD (Frequency Division Duplex) and TDD (Time Division Duplex) duplexing methods are included in the LTE specifications. For FDD operation, the generic frame structure is applicable to both downlink and uplink. The generic frame structure used with FDD is described briefly in detail. The duration of LTE frames are of 10 msec. The frames are further divided into 10 subframes; each subframe has the duration of 1.0 msec. The subframe further consists of two slots, each of having 0.5 msec long duration. So overall the frames consist of 20 slot periods of 0.5 msec. Each time slot may contain either 6 or 7 OFDM symbols, corresponding to a normal or an extended cyclic prefix in use. The LTE generic frame structure for FDD is depicted in Figure-2 (Dahlman *et al.,* 2007; 3GPP TS 36.201, 2009).

LTE PHY Downlink Resource Grid:

The downlink (DL) transmission signal in each time slot is managed by a resource grid of NBW subcarriers for the duration of “Nsymb” OFDM symbols. The resource grid for the downlink is presented in Figure-3 (3GPP TS 36.201, 2009).

Resource Element (RE):

In Figure-3, each box with in the resource grid stands for a single subcarrier for one symbol duration or period, named as a Resource Element (RE). RE is alternatively the smallest time-frequency unit used in the downlink transmissions (3GPP TS 36.212, 2009).

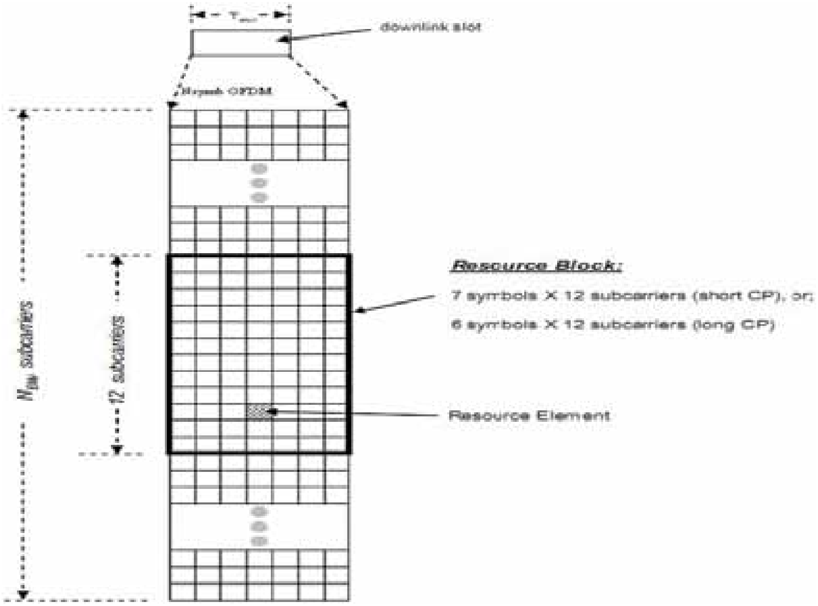

Fig. 3: LTE Downlink Resource Grid

Table 1: Physical Resource Blocks for Different Available Bandwidths

Available Bandwidth (MHZ)	1.25	2.5	5.0	10.0	15.0	20.0
Subcarrier spacing (KHz)	15	15	15	15	15	15
PRBs bandwidth (KHz)	180	180	180	180	180	180
Available PRBs	6	12	25	50	75	100

Resource Block (RB):

A Resource Block (RB) is constituted of a group of 12 subcarriers adjacent in frequency domain and one slot in time. The RBs demonstrate the mapping of the resource elements to physical channels. The bandwidth available for LTE PHY is divided into Physical Resource Blocks (PRBs). A PRB represents the smallest unit allocated by the eNodeB scheduling mechanism. The transmission bandwidth of the LTE system determines the total number of subcarriers available at the physical layer. The Table-1 shows the number of PRBs for the different bandwidths. The Physical Resource Blocks (PRBs) are numbered from 0 to (NRB -1). The relationship between the nPRB, PRB number in frequency domain and the Resource Element (RE) in a time slot is as expressed as follows (Dahlman *et al.,* 2007).

nPRB = mod [k/Nsc]

MIMO Configurations:

For the LTE downlink MIMO transmission two configuration are available. The first is 2*2 MIMO antennas configuration, which is assumed as the fundamental MIMO configuration for the LTE. In this configuration 2 antennas are used at the transmission end and similar to antennas are used at the reception end. And configuration of 4*4 antennas is also considered for the LTE (3GPP TS 36.201, 2009; Juho Lee, *et al.,* 2009). The following are the main LTE downlink multiple antenna schemes;

Spatial Multiplexing:

It allows transmitting data from different application flows concurrently on the same Resource Block (RB) by exploiting the spatial dimension of the radio channel. These transmitted data streams may belong to a single user MIMO (SU-MIMO) or multiple users MIMO (MU-MIMO). The spatial multiplexing is possible only if the radio channel allows it.

Transmit Diversity:

Long term Evolution supports transmit diversity with two or four antennas. In transmit diversity, multiple antennas with the transmit power divided among these antennas and the same signal is sent from these multiple antennas. To exploit the gains from independent fading paths among the multiple antennas, a certain level of coding is utilized. Transmit diversity is needed in system such as cellular systems where more power, space and processing capability is available on the transmitter side versus the receiver side. Transmit diversity design depends on whether or not complex channel gain is known at the transmitter or not known. When this complex channel gain is known the system is very similar to receiver diversity. Without this channel knowledge, transmit diversity gain require a combination of time and space diversity via a novel technique called the Alamouti scheme (Alamouti, 1998). To address the problem of decoding complexity, Alamouti STBC (Space Time Block Coding) scheme with two antennas is used for transmission.

Receive Diversity:

For the UE, the downlink receive diversity scheme is mandatory. Fundamentally this kind of diversity defines the receiver capability for the baseline performance requirements. Maximal Ratio Combing (MRC) of the received streams is typically used to ameliorate the SNR when the channel conditions are worse. The receive diversity is able to provide the little gain in good conditions. Maximal Ratio Combining (MRC) is probably the optimum and best technique for combining diversity received signals (3GPP TS 36.211, 2009).

Pre-coding:

For maximizing the received SNR, the signals transmitted from multiple antennas are weighted. LTE uses pre-coders that perform phase corrections only and do not handle amplitude changes. The transmission modes of the Physical Downlink Shared Channel (PD-SCH) include the open loop spatial multiplexing and closed loop spatial multiplexing. These modes employ pre-coding using a “codebook” to formulate transmission layers. A set of predefined pre-coding matrices constitute the codebook. The size of the set is a trade-off between the correctness of the resultant transmitted beam direction and the total number of signaling bits needed to specify a certain matrix in the codebook (3GPP TS 36.201, 2009; Larmo *et al.,* 2009).

Layer Mapping:

Layer mapping along with pre-coding is used in MIMO based communications. Layer Mapping describes the process how multiple transmitter antennas are used. MIMO systems are defined as “Ntx * Nrx”. For LTE defined configurations are 1*1, 2*1, 2*2, 3*2, and 4*2. It is to be noted that there can be four transmitting antennas whereas there may only be a maximum of two receivers. Therefore, there is possibly a maximum of only two spatially independent data streams present in LTE systems (3GPP TS 36.211, 2009). The complex symbols for modulation corresponding to each code word to be transmitted are then mapped onto one or several of the spatial layers.

For instance, the complex valued symbols d^q (0),….., d^q (M^q_{symbol} -1) for the code word ‘q’ would be mapped onto the layers; x(I)=[$x^{(0)}$ (i)... $x^{(v-1)}$ (i)], i=0,1,..., M^{layer}_{symbol} -1 where *v* is the number of layers and M^{layer}_{symbol} is the number of modulation symbol per layer (3GPP TS 36.201, 2009; Larmo *et al.,* 2009).

Modulation - Higher Order (OFDM and QAM):

The average and peak bit-rates and spectrum efficiency can only be optimized by introducing advanced modulation schemes. Higher order modulation exploits localized geographical channel condition to optimize the coverage and therefore providing high data rates (3GPP TS 36.211, 2009). LTE downlink physical layer works with different modulation schemes, depending on the data rates and coverage circumstances. The introduction of OFDM with 16QAM and 64 QAM improves robustness against interference and eventually increases the bit-rates. Modulation schemes considered in this study are QPSK and 16-QAM (Larmo *et al.,* 2009).

IV. Simulation Results and Analysis:

In this work, the performance of LTE downlink physical layer has been analyzed using the simulation model developed in MATLAB. A number of simulation scenarios have been considered to study the impact of using higher order modulation schemes and several MIMO configurations in both AWGN and Rayleigh Channels. For all simulation scenarios, we evaluate BER as a function of SNR in dBs. Table-1 lists the LTE Downlink Physical Layer parameters used in this study (3GPP TS 36.201, 2009). Results for the following scenarios are presented in this section;

- Performance of QPSK-OFDM and 16-QAM-OFDM in AWGN and Rayleigh Channels
- Comparison of QPSK-OFDM and 16-QAM-OFDM in AWGN and Rayleigh Channels
- Impact of MIMO Configuration for QPSK-OFDM and 16-QAM-OFDM in AWGN and Rayleigh Channels

Table 2: LTE Downlink Physical Layer Parameters

Parameters	Values
Bandwidth	5 MHz
FFT size	512
Symbol rate	21.4M symbols/sec
Channel coding	Rate 3/4 convolutional coding
Transport Block size	4500(16-QAM),2250(QPSK)
Layer mapping order	2 layers
Cyclic Prefix (CP)	144 symbols
Total OFDM symbols	12
MIMO technique	Space Time Block Coding
MIMO receiver	Alamouti/MRC
Modulation	QPSK,16-QAM
Channel estimation	Ideal
Channel used	AWGN, Rayleigh
Precoding	According to Release 8[TS 36.211]
Antenna Schemes	SISO 1X1,MIMO 2X2,3X2

Performance of QPSK-OFDM and 16-QAM-OFDM in AWGN and Rayleigh Channels:

Figure-4 shows the performance curves of QPSK-OFDM modulation in AWGN and Rayleigh channels. It can be observed that the performance of QPSK-OFDM in AWGN is much better than that in Rayleigh channel. For example at an SNR of, the BER is about 60 times higher in Rayleigh channel than that in AWGN channel. Similarly, Figure-5 depicts the performance curves for 16-QAM OFDM modulation in AWGN and Rayleigh channels without diversity. The performance of 16-QAM OFDM in AWGN is much better than in Rayleigh channel, primarily due absence of fading effect in AWGN.

Comparison of QPSK-OFDM and 16-QAM-OFDM in AWGN and Rayleigh Channels:

Figure-6 shows the performance of OFDM with QPSK and 16-QAM modulations in AWGN channel. Figure-7 shows the performance of OFDM with QPSK and 16-QAM modulations in Rayleigh channel. It can be seen that QPSK performs better in both types of channels; however, 16-QAM provides much higher throughput as compared to QPSK. The higher bit error rate experienced by 16-QAM can be compensated by efficient channel coding. Further, if channel conditions become better, 16-QAM or higher level modulation is preferable due to higher throughput offered. In case of bad channel conditions, the use of more robust QPSK is desirable although the through put would be reduced.

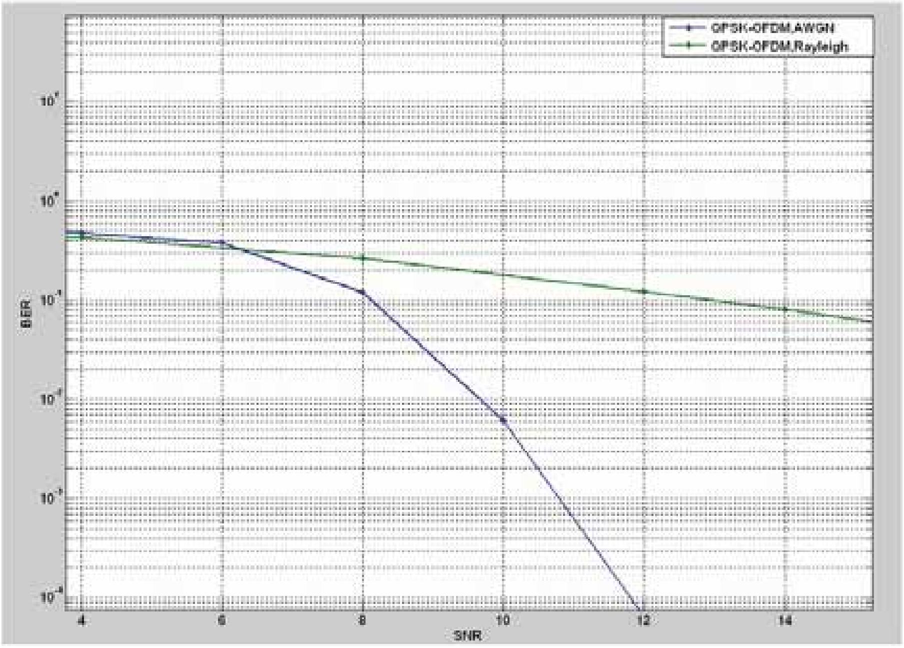

Fig. 4: Performance curves of QPSK-OFDM in AWGN and Rayleigh Channels

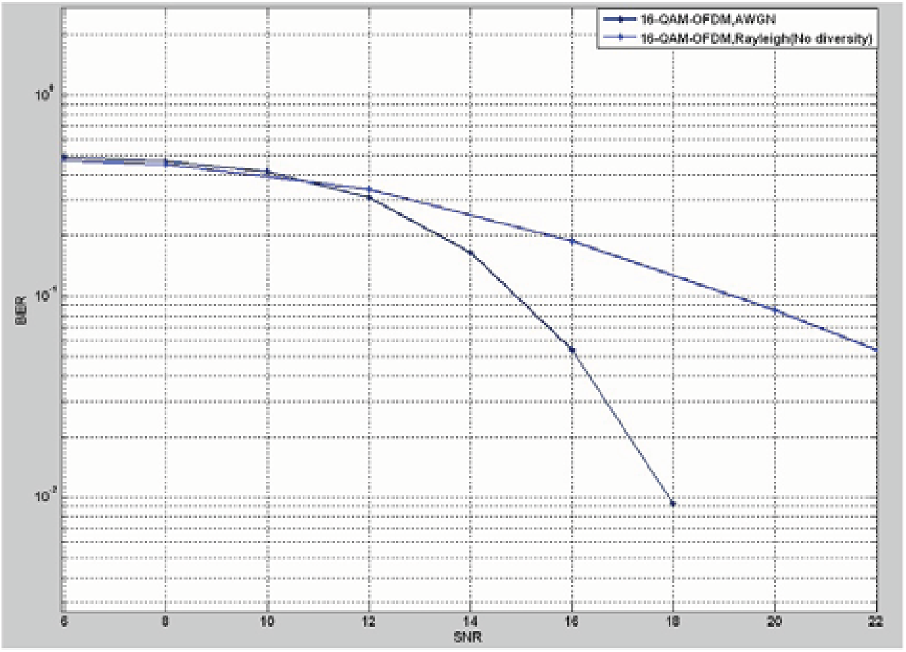

Fig. 5: Performance curves of 16-QAM-OFDM in AWGN and Rayleigh Channels

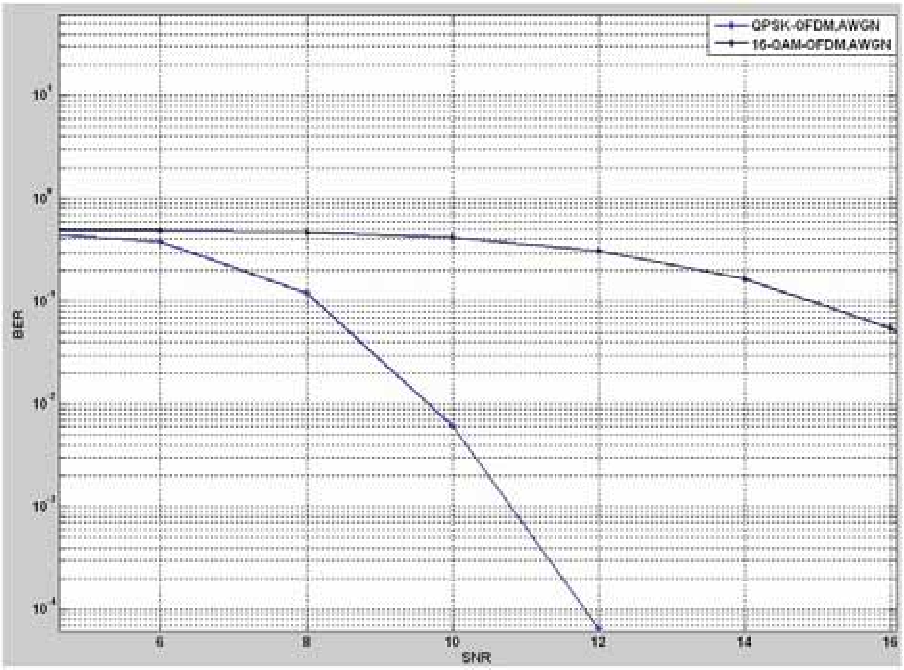

Fig. 6: Performance of QPSK-OFDM and 16QAM-OFDM in AWGN Channel

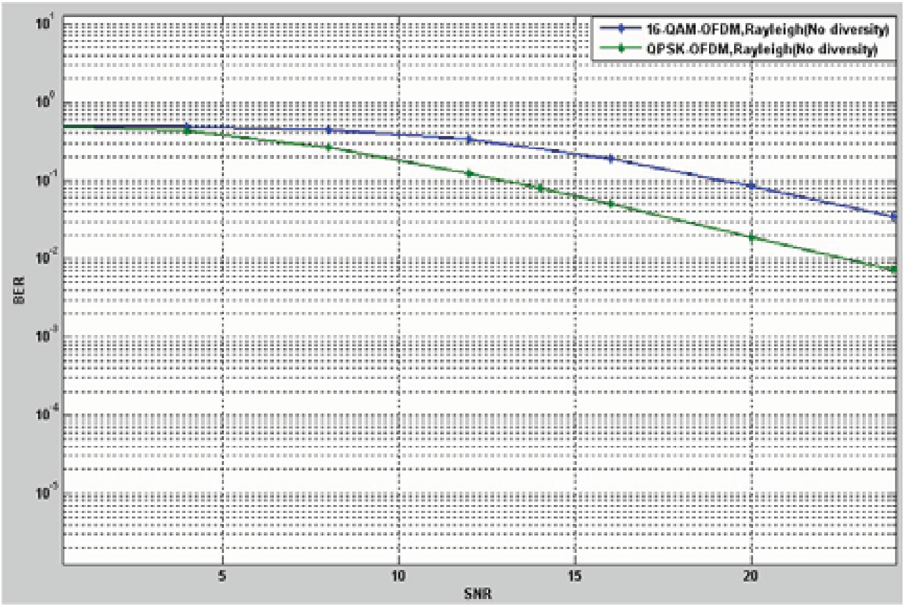

Fig. 7: Performance of QPSK-OFDM and 16QAM-OFDM in Rayleigh Channel

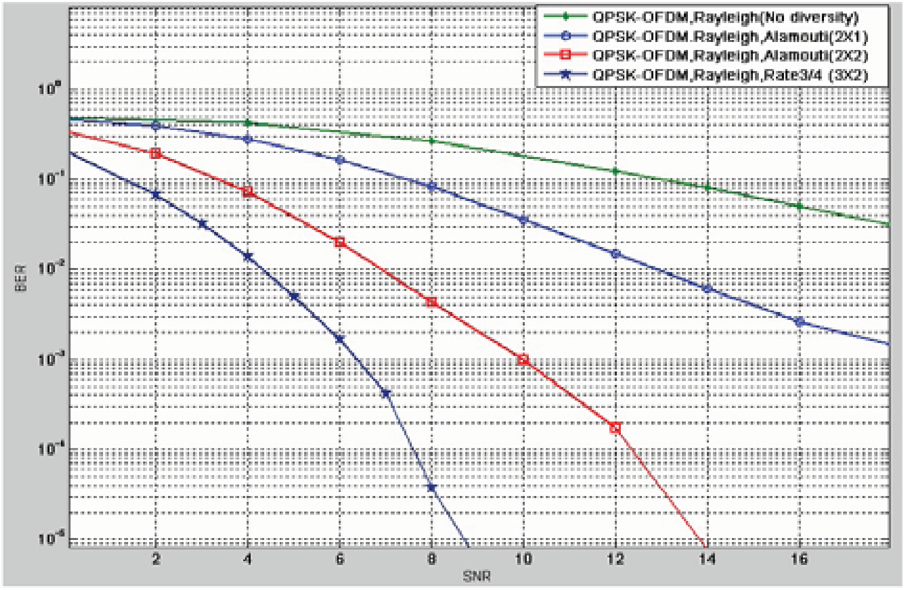

Fig. 8: Performance of 16-QAM-OFDM for different MIMO Configurations in AWGN Channel

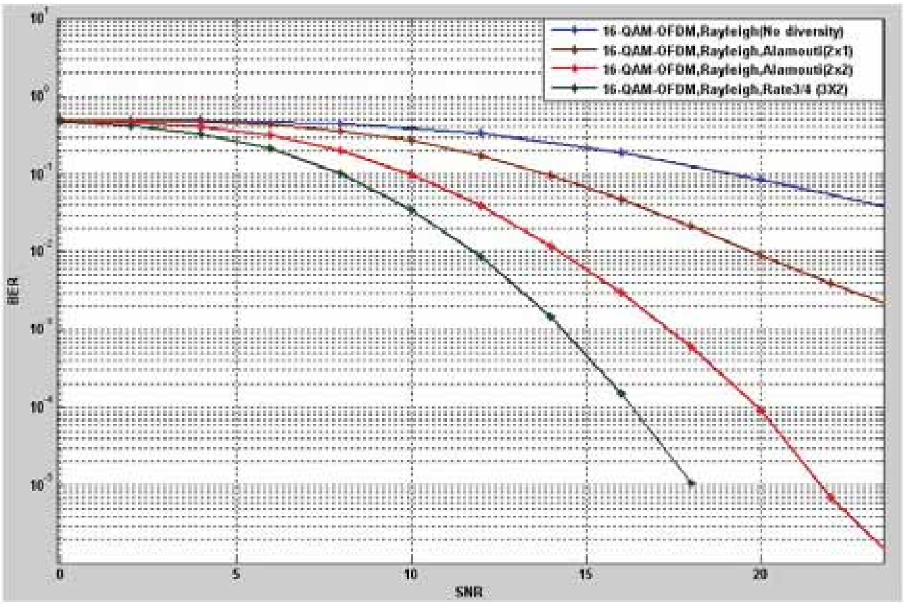

Fig. 9: Performance of 16-QAM-OFDM for different MIMO Configurations in Rayleigh Channel

Impact of MIMO Configurations for QPSK-OFDM and 16-QAM-OFDM in AWGN and Rayleigh Channels:

Figure-8 and Figure-9 show impact of various MIMO configurations on the performance of LTE physical layer in terms of BER and SNR for the two modulation combinations, QPSK-OFDM and 16-QAM-OFDM. From Figure-8, it can be seen that incase of QPSK-OFDM, for no diversity scenario, a BER of 10^-1 is achieved at 14 dB whereas MIMO 2X1 configuration provides same BER at 8dB.Thus 2X1 configuration gives an improvement of approximately 6 dB over no diversity scheme. 2X1 MIMO configuration gives BER of 10^-2 at 14dB SNR value while 2X2 configuration almost same BER performance is experienced at approximately 8 dB of SNR. Thus an improvement of 6 dB is achieved using 2X2 MIMO configuration. Further, for the 3X2 MIMO configuration, a BER of 10^-2 is observed at 5 dB and for the 2X2 configuration, 8 dB of SNR provides the same BER. Thus 3X2 configuration offers an improvement of approximately 3dB over 2X2 configuration. Similar performance is observed for the case of 16-QAM-OFDM as depicted in Figure-9. It shows that for no diversity case BER of 10^-1 is achieved at 20 dB whereas MIMO 2X1 configuration affords approximately the same BER at an SNR of 14 dB. Thus 2X1 configuration offers an improvement of approximately 6 dB over no diversity scheme. Moreover, for the 2X1 MIMO configuration, a BER of 10^-1 is experienced at 14 dB of SNR while for 2X2 configuration, almost same BER value is attained at approximately 10 dB value of SNR. Thus an improvement of 4 dB is achieved using 2X2 MIMO configuration. Also, 3X2 MIMO configuration results in a BER of 10^-1 at 8dB whereas the ER performance is achieved for an SNR of 10 dB. Thus 3X2 configuration offers an improvement of approximately 3dB over 2X2 configuration, similar to the case of QPSK-OFDM. This clearly indicates that the performance can be significantly increased with advanced MIMO techniques.

V. Conclusions:

This work has focused on the analysis of Long Term Evolution (LTE) downlink physical layer transmission. For this purpose, a simulation model has been developed in MATLAB that includes all the required physical layer functionality for LTE downlink transceiver. The major emphasis in this work has been on the evaluation of the impact of Orthogonal Frequency Division Multiplexing (OFDM) with higher order modulations such as 16-QAM and advanced spatial multiplexing techniques like MIMO in both the AWGN and Rayleigh channels. The results have been reported in terms of Bit Error Rate (BER) vs. SNR in dBs. It has been observed that with increasing modulation order, the bit rate achieved is higher; however, the BER increases as well for the same range of SNR values. This is primarily because of the fact that the distance between the symbols decreases for higher order QAM that results in a higher symbol errors, thus increased BER. It is to be noted that the BER can be greatly improved with advanced channel coding techniques such as Turbo and LDPC codes. Similarly, it has been shown that as number of antennas is used at transmitter and receiver or the diversity order increases, the BER performance is significantly improved. The higher levels of spatial diversity offered by the increasing MIMO configurations translates into improved BER performance or can be translated into higher throughput for the same BER.

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