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A Simulation Design of LTE Communication System under Adaptive Modulation Schemes

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Abstract:
Long-Term Evolution (LTE) is a standard for high-speed wireless communication for mobile phones and data terminals, based on the GSM/EDGE and UMTS/HSPA technologies. It increases the capacity and speed using a different radio interface together with core network improvements. The LTE standard uses three different modulation schemes to adapt to various channel conditions in order to improve achievable data rates. These modulation schemes are the QPSK, 16-QAM and 64-QAM. This paper presents an overview of a LTE digital communication system. A Simulation model, designed in order to study the effects of the different modulation schemes on the basis of BER performance with an AWGN channel model. Different subsystems within the transmitter and receiver blocks are implemented in MATLAB. It is noted that the LTE system uses different coding techniques to offer reliable and secure services to the users. Depending on the assumed channel condition (clear, medium clear or noisy), the 64-QAM, 16-QAM or QPSK modulation scheme, on the transmitter side as well as the corresponding demodulation scheme, on the receiver side is used. Based on the recovered data bits, the obtained bit error rates are analyzed, compared and discussed.

Keywords: LTE; QPSK; 16-QAM; 64-QAM; AWGN, Turbo coding, Bit-level scrambling, BER System.

I. INTRODUCTION

The simulation of the LTE communication system at its Physical Layer is crucial in order to assess and understand why and how the selection of a particular modulation scheme can affect its reliability in terms of its BER performance. One of the main distinguishing features of the LTE technology remains its ability to provide very high capacity and throughput services. In order to maintain such important features, the LTE system has to adapt its modulation scheme to the communication channel's conditions. This adaptation of the LTE modulation scheme impacts on the reliability of the system since it affects its BER performance [1]. This paper presents a mathematical foundation and associated algorithms of the LTE enabling technologies, such as Turbo channel coding and bit-level scrambling. This design study uniquely contributes to the understanding of the LTE digital communication PHY models and the improvement of the BER performance of the system by means of Turbo channel coding. The focus of this paper is then turned towards implementing a fully operational LTE digital communication Simulink model by synchronizing and integrating its different subsystems. This study particularly evaluates the impact of both the channel conditions based adaptive modulation and the Turbo channel coding on the BER performance of the system. As opposed to other related works, this design explores the isolated effect of LTE changes in the modulation schemes on the BER of the system. It then after explores the Combination effects of modulation schemes adaptation and Turbo channel coding on the reliability of the communication System evaluated by means of the obtained BER performance. A theoretical BER performance model for the AWGN channel model is first analysed before the simulated BER results are obtained from the simulation of the fully integrated LTE Simulink model. The obtained simulation results for the three modulation schemes are analysed, discussed and compared to the theoretically expected results before being compared to each other.

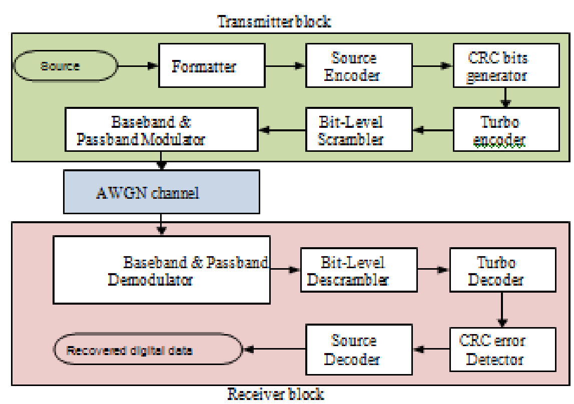

Figure.1. LTE digital communication system block diagram

The LTE system as illustrated in FIGURE 1comprises of:

1. A transmitter block made of, from source to the channel, a formatter, a Mu-law compressor, CRC error detector, Turbo channel encoder, bit-level scrambler, NRZ baseband modulator and a selection based pass band modulator subsystems.
2. The AWGN defined by its noise variance parameter.
3. A receiver block made of, from channel to destination, a pass band demodulator, a bit-level descrambler, a Turbo channel decoder, a CRC error detector and a Mu-law expander subsystems.

II. MATHEMATICAL MODEL AND ALGORITHMS

A. Formatting

In a digital communication system, formatting is the process of converting the source information to a format that is compatible with the digital signal processing. When the source information is analogue, formatting simply becomes the analogue-to-digital conversion. In a digital communication system, source information can also be textual data. In such a case, formatting is simply reduced to character coding [2]. Formatting of an analogue signal consists of three main processes namely:

1. **Sampling:** An analogue signal *x(t)* sampled at a rate f_S(meaning$Ts = f_S^{-1}$) generates a sequence

$$x(kTs) = x(t)|_{t=kTs} \quad (1)$$

2. **Quantization:** consists of mapping a set of infinite precision sampled values to a set of finite precision numbers. With a maximum(peak) positive analogue voltage $V_p$and a quantization step voltage q, we get:

3.

$$\left[-V_p + \left(\frac{iq}{2}\right)\right] \leq x(kTs) < \left[-V_p + \left(\frac{(i+1)q}{2}\right)\right] \quad (2)$$

if $\left|x(kTs) - \left(-V_p + \left(\frac{iq}{2}\right)\right)\right| < \left|x(kTs) - (-V_p +\right.$ *i+1)q2)*

then$x(kTs) \equiv -V_p + (\frac{iq}{2})$

else$x(kTs) \equiv -V_p + (\frac{(i+1)q}{2})$ (3)

4. **Binary encoding:** This part consists of converting the quantized, finite length value into a binary number. For a resolution n, the quantized value *q_val* gives:

$$\text{Bin\_val} = \text{Q} - \text{val} * \left(\frac{2^n - 1}{V_p}\right) \quad (4)$$

B.Turbo channel coding

Turbo channel coding is the basis of channel coding as specified in the LTE standard. It belongs to the category of channel coding algorithms known as parallel concatenated convolutional coding [3]. Its mechanism of operations can be explained as follows: Considering a (N, K) Turbo coding with $R_c=1/3$

$$\text{N} = (\text{K} + \text{Trellis}) * 3 \quad (5)$$

The Trellis structure of the constituent LTE Turbo encoder isdescribed in the Z-plane by the two following polynomials:
$G_0(z) = 1 + z^{-2} + z^{-3}$ and $G_1(z) = 1 + z^{-1} + z^{-3}$ (6)

Each input bit S_k gives [S_k, P_{1k}, P_{2k}] according to FIGURE 2
The two parity bits P_{1k},P_{2k}can be derived as follows:

From FIGURE 2,
let$m_{1k} = S_k + (S_{k-3} + S_{k-2})$,then$P_{1k} = m_{1k} + m_{1(k-3)}$ (7)

In order to generate the second parity bitP_{2k} , the input data bit$S_k$goes through a Turbo code interleaver. The LTE turbo coder is a contention-free coder that uses a QPP interleaver, which substantially improves the turbo code performance by streamlining the memory access in interleaving operation [4]. The Turbo code interleaver consists of a permutation operation performed by means of two user-defined functions of *Sk* ($f_1$andf_2) described as follows:

$$perm_k = (f_1 k + f_2 k) mod(K) \quad (8)$$

From (FIGURE 2),
let $m_{2k} = perm_k + (perm_{k-3} + perm_{k-2})$ (9)

then$P_{2k} = m_{2k} + m_{2(k-3)}$ (10)

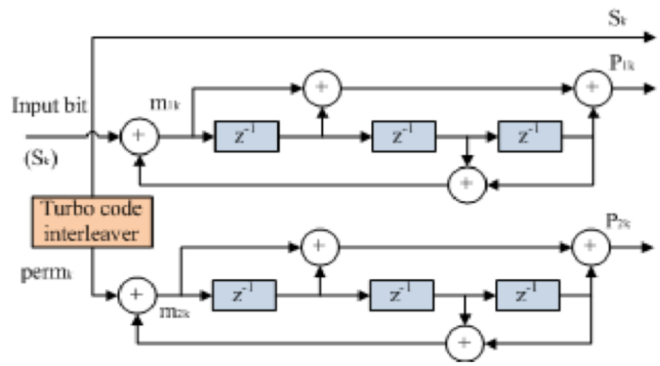

Figure.2. LTE Turbo Encoder Block Diagram

C.Bit-level scrambling

In LTE downlink processing, the codeword bits generated as the outputs of the channel coding operation are scrambled by a bit-level scrambling sequence. Various scrambling sequences are used in neighbouring cells to ensure that the interference randomization and separation of transmissions from different cells prior to decoding [1].

First, unique pseudo-random sequences are generated using the Gold sequence described as follows:

$$\text{G} = \{x_1, x_2, x_3, \dots \dots, x_{31}\} \quad (11)$$

Then, a bit level multiplication of the sequence by the input data followed by the XOR operation is performed as follows:

$$p_1(x) = x^{31} + x^3 + 1 \quad (12)$$

$$p_2(x) = x^{31} + x^3 + x + 1 \quad (13)$$

The output bit-level scrambled data sequence is given by:

$$\text{Scra\_data} = \text{XOR}\,[p_1(x), p_2(x)] \quad (14)$$

III. LTE SIMULINK MODEL IMPLEMENTATION

The LTE digital communication system as globally described in Fig. 1 has been implemented in the Simulink block diagram environment for real-time simulation. The implementation has been performed in a multiple models format. Each model has been designed to simulate the dynamic behaviour of every single subsystem and obtained results at each stage are each time visualized for analysis purposes. The implementation has been performed by means of some blocks from the different Simulink toolboxes and mainly from the communication and signal processing toolboxes. Due to the complexity of their operations, some other algorithms have been implemented by means of user-defined functions embedded in the different Simulink models. The various parameters settings at all stages of the Simulink model are provided in TABLE I in the simulation section.

A Transmitter

1. **The formatter**: This subsystem, illustrated in FIGURE 3, is made of two main all Simulink built-in blocks namely:
   - ***a) The Zero-Order Hold block:*** Used for both sampling and-holding as well as quantization processes.
   - ***b) The Uniform Encoder block:*** configured to perform the binary coding. The *Integer to Bit Converter block* is added after the Uniform encoder block in order to convert the encoded integer output data from the uniform encoder to the binary format.
2. **The source encoder**: This subsystem is implemented by means of a single *Mu-Law Compressor* built-in Simulink block.
3. **The CRC bit generator**: This error-detection section of the channel coding subsystem is implemented by means of the *General CRC Generator* built-in Simulink block, implemented with a single checksum per frame and a generator polynomial.
4. **The LTE Error-correction Turbo encoder:** This subsystem is also implemented by means of an appropriately configured built-in Simulink block named *Turbo Encoder* of which the configuration parameters are provided in TABLE I.
5. **The Bit-level scrambler**: This subsystem, illustrated in FIGURE 4, is implemented by means of a user-defined embedded MATLAB function of which the pseudo-code is provided in FIGURE 5

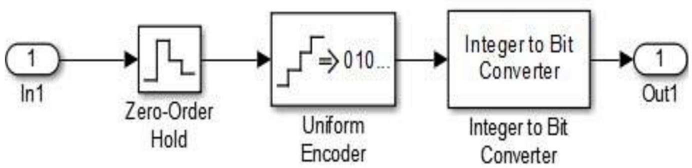

Figure.3. **LTE Transmitter Formatter Subsystem Illustration**

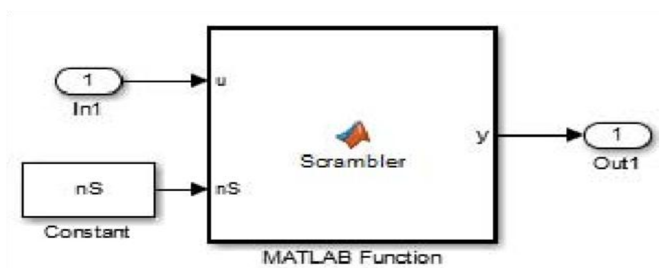

Figure.4. **Bit-Level Scrambler Subsystem**

```
1. Initialise parameters: RNTI,nS,q & NcellID
2. Compute initial condition: C_init=
   RNTI*(2^14)+q*(2^13)+floor(nS/2)*(2^9)+NCellID
3. Convert initial states to binary format:
   initStates=Int2Bit(c_init)
4. Generate the scrambling sequence:
   seq=Gold sequence generation
5. Scramble input data using the generated Gold
   sequence to produce output: y=xor(u,seq)
```

Figure.5. **Bit-Level Scrambler Algorithm Pseudo-Code**

6. **The Baseband modulator**: The NRZ baseband modulation subsystem, used in this case, is implemented by means of a user-defined embedded MATLAB function of which the pseudo-code is provided inFIGURE6.

```
1. if bit is HIGH
       SET output signal to Positive Amplitude

   else
       SET output signal to Negative Amplitude

2. Maintain output signal state for bit time
   period (Tb)

3. Return to step 1
```

Figure.6. **LTE NRZ Baseband Modulation**

7. **The Passband Modulator**: To implement the LTE channel conditions-based Passband modulator, a *LTE SWITCHED PASSEBAND_MODULATOR* Simulink subsystem block is designed. It uses a multiport switch controlled by the variable *"Mode"* parameter to switch between the outputs of the QPSK, 16-QAM or 64QAM modulator built-in Simulink blocks; as illustrated in FIGURE 7.

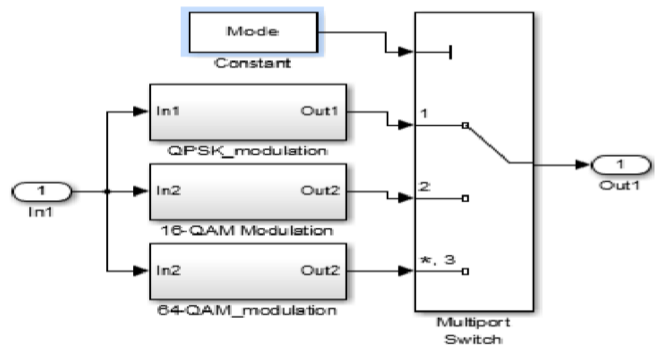

Figure.7. LTE Channel Conditions-Based Switched Pass band Modulation

B. Channel

Although no model can perfectly describe a channel environment because physical channels are stochastic by nature, they strive to obtain as much precision as possible.[5]. Due to the fact that, the channel model is not the focal point of the study in this paper, to reduce the complexity of the whole simulation, the Additive White Gaussian Noise channel has been used for simulation purposes. The implementation of the AWGN noise channel in Simulink, as illustrated in FIGURE8, has been performed by means of built-in AWGN Simulink model. It has been modelled statistically and described by means of its noise variance parameter provided in Table I.

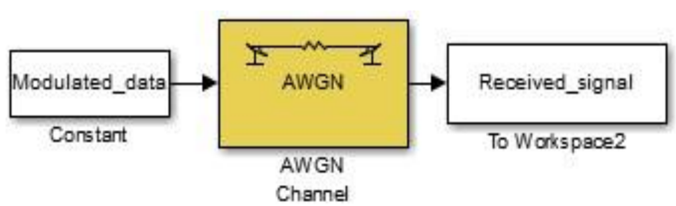

Figure.8. AWGN Channel Simulink Implementation

C. Receiver

The Simulink implementation of most of the receiver subsystems basically consists in the opposite operations of the processes implemented on the transmitter side. However, it is important to notice certain particularities observed during the implementation of the receiver while carrying on this particular study on the LTE digital communication system.

- First, the LTE Turbo decoder is based on the use of two *A posterior Probability (APP)* decoders and two interleavers in the feedback loop [6].
- Secondly, the same trellis structure found in the Turbo encoder must be used when implementing the APP decoder.
- Thirdly, the performance and computational complexity of a Turbo decoder is based on the number of iterations performed [1].
- Lastly, the type of bit level descramble used whether soft or hard decision based must always match the type of Turbo decoder used (soft or hard).

The bit-level descrambler has once again been implemented using user defined embedded MATLAB function of which the pseudo-code is depicted in FIGURE9.

```
1. Initialise parameters: RNTI,nS,q & NcellID
2. Compute initial condition: C_init=
   RNTI*(2^14)+q*(2^13)+floor(nS/2)*(2^9)+NCellID
4. Convert initial states to binary format:
   initStates=Int2Bit(c_init)
4. Generate the descrambling sequence:
   seq= Gold sequence generation
5. if descrambler inputs are LLRs  then convert seq
   to a bipolar format seq=1-2*seq
6. Descramble the sequence u : y=u*seq
```

Figure.9. Soft-Decision Bit-Level Descrambling Process

All the other subsystems have been implemented by means of built-in Simulink blocks. As most Simulink communication system toolbox blocks come in pairs, the blocks used on the receiver side correspond to the blocks used on the transmitter side and perform their reverse processes.

IV. SIMULATION

The simulation of the LTE digital communication system has been performed by means of both MATLAB scripts and multiple Simulink models, each implementing the behaviour of a particular subsystem. The logic behind the sequential simulation process, that describes the content and purpose of the simulation script, is illustrated in FIGURE10.

```
Subsystem k
1. Initialise parameters
2. Run(simulate) Subsystem k model
3. Save and visualize obtained results
Subsystem k+1 …
```

Figure.10. LTE System Simulation Script Process

Simulink is integrated with MATLAB and data can be easily transferred between programs [7]. Table I below captures the key simulation aspects.

TABLE.1. SIMULATION FEATURES

Subsystems	Features		
	Simulink block	***Parameters***	***Implementation***
Source signal	Signal Generator	Wave form	Sine modelling voice
		Time	Use simulation time
		Amplitude, Freq	1 V, 1 KHz
Formatter	Zero-Order Hold	Fs	1 MHz
	Uniform Encoder & decoder	Peak, Resolution	1 V, 8 bits
	Integer-to-Bit Converter	Bits-per Integer	8 bits
Source encoder	Mu-Law Compressor & expander	Mu-value	255
Channel encoder	General CRC Generator & detector	Gen. polynomial	[1,1,0,0,1,1,0,0,1]
		Number of redundant bits	8 bits
	Turbo Encoder & decoder. (With frame segmentation into Codeblocks).	Trellis structure	[0,3;0,3;1,2;1,2; 1,2;1,2;0,3;0,3]
		Interleaver indices	[1,20,15,34,29,48,43,14, ,28,23,42,37,8,3,22, 17,36,31,2,45,16,11,30, 25,44,39,10,5,24,19,38, 33,4,47,18,13,32,27,46, 41,12,7,26,21,40,35,6]
		Coding rate	1/3
baseband modulator	NRZ modulator & demodulator	Bit period (Tb)	1 second
Channel	AWGN channel	Initial seed, Noise variance	67, variable
Global system parameters		Frame size	40
		Simulation time per frame	1 ms

V. RESULTS AND DISCUSSION

In order to evaluate the performance of the designed LTE communication system, the obtained results are presented and discussed in this section. The source signal is monitored as it moves from the transmitter to the receiver in order to understand the different involved concepts and properly assess the end results [5]. In order to achieve the objectives of this study, simulations have been conducted for the following different scenarios:

- The non-coded BER performance for the three different modulation schemes (QPSK, 16-QAM and 64-QAM).
- The Turbo-coded BER performance for the QPSK modulation scheme.
- The Turbo-coded BER performance for the 16-QAM modulation scheme as well as the Turbo-coded performance for the 64-QAM modulation scheme.

In all the above mentioned scenarios, the data bits recovered at the receiver side are synchronously compared to the corresponding transmitted bits. All differences between them are detected and counted. At the end of the transmission of every data block, for different SNR (dB) values, the experimental outcome is statistically analysed and the error probability is deducted. Given an array of bit energy to noise variance values (*EbN0*), the number of bits per symbol (*k=2 for QPSK, k=4 for 16-QAM and k=6 for 64-QAM)* and the coding rate *R*, for coded scenarios, the SNR values are computed as follows:

For the non-coded scenarios,

$$\mathrm{SNR(dB)} = \mathrm{EbN0} + 10log_{10}(k) \qquad (15)$$

For Turbo-coded scenarios:

$$\mathrm{SNR(dB)} = \mathrm{EbN0} + 10log_{10}(k) + 10log_{10}(R) \qquad (16)$$

With:

Num_tails = 2*log2(Trellis_number_of_states) (17)

And:

$$\mathrm{R} = \frac{(blck\_size + redundant\_bits)}{3*(blck_{size} + redundant_{bits}) + (2*Num\_tails)} \qquad (18)$$

A. Non-coded simulation scenarios

The results obtained by simulating the LTE system without any Turbo-channel coding subsystem integrated in the model are presented in FIGURE11.

Non-coded BER probability curves under QPSK,16-QAM & 64-QAM

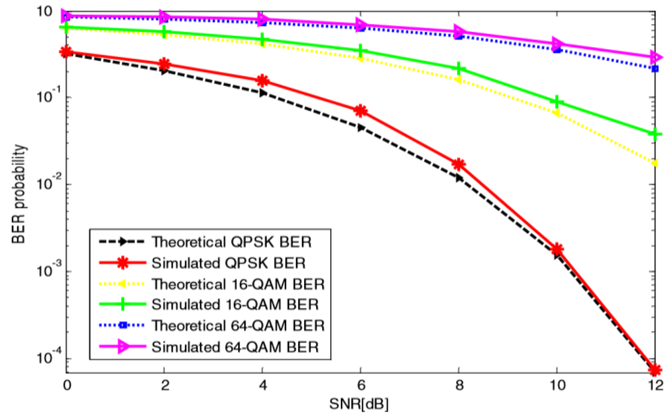

Figure.11. Non-Coded BER Performance

As we can clearly observe in FIGURE11 above, the non-coded LTE system's bit error rate performance deteriorates as the modulation constellation becomes denser. The probability of bit error rate increases as we move from QPSK (2 bits per symbol representation) to the 16-QAM (4 bits per symbol representation) and finally to the 64-QAM (6 bits per symbol representation) modulation schemes. This explains why the LTE switched channel-conditions based adaptive modulator makes use of the 64-QAM modulation in very clear channel conditions where the signal's strength is by far stronger than the noise signal; in order to provide the user with the benefits of high data throughput with guaranteed reliable communication. As the channel conditions deteriorate, the adaptive LTE modulator automatically reduces the constellation density of its modulation scheme by a factor of (1/4) to a 16-QAM modulation scheme in order to balance communication throughput and reliability in such a way that the user fairly benefit from network's services depending on his communication environment. The same principle applies for worst case channel-condition scenarios where high data rates are just trade-off by reliability by using a much less denser modulation scheme (QPSK). As we can observe in FIGURE11, for the same channel conditions and the same signal's power, the LTE system using QPSK modulation scheme is much more reliable than the 16QAM which performs better than the 64-QAM. In other terms, it requires higher signal's power for the 16-QAM modulated LTE system and even much higher signal power for the 64QAM modulated LTE system to achieve the same BER performance as the QPSK-modulated LTE system under the same channel conditions. From the numerical BER values obtained from the simulation, at a value of *SNR=8 dB*; the non-coded QPSK, 16QAM, 64-QAM exhibit $|0.012 - 0.017| = 0.005$, $|0.22 - 0.1611| = 0.0589$, $|0.5095 - 0.578| = 0.0685$, absolute error margins, respectively. This means that the simulated results closely follow the theoretical (ideal) results, and also implies that the QPSK BER simulation scenario is much more accurate than the 16-QAM and 64-QAM scenarios although all the absolute error margins still prove that the overall model simulation was conducted with precision. The closeness between simulated and ideal (theoretical) results also validates the simulated results.

B. Turbo-coded simulation scenarios

Theoretically, the error correction capability of the Turbo channel coding is expected to improve the BER performance of the system. The simulation of the LTE system including the Turbo channel coding subsystem for each of the three LTE modulation schemes (QPSK, 16-QAM and 64-QAM) resulted into the BER performance provided in Table II.The same BER performances are also illustrated in FIGURE12, FIGURE13 and FIGURE14 respectively.

TABLE.2. TURBO-CODED QPSK, 16-QAM AND 64-QAM BER PERFORMANCE RESULTS

QPSK Modulation SNR (dB)	0	2	4	5	5.5	
Simulated BER	0.415	0.21	0.11	0.03	0.0001	
16-QAM Modulation SNR (dB)	0	2	4	5	6	7
Simulated BER	0.65	0.541	0.419	0.3522	0.031	0.01
64-QAM Modulation SNR (dB)	0	2	4	6	7	7.5
Simulated BER	0.86	0.817	0.7259	0.6309	0.398	0.251

Non-coded vs Turbo-coded BER performance with QPSK modulation scheme

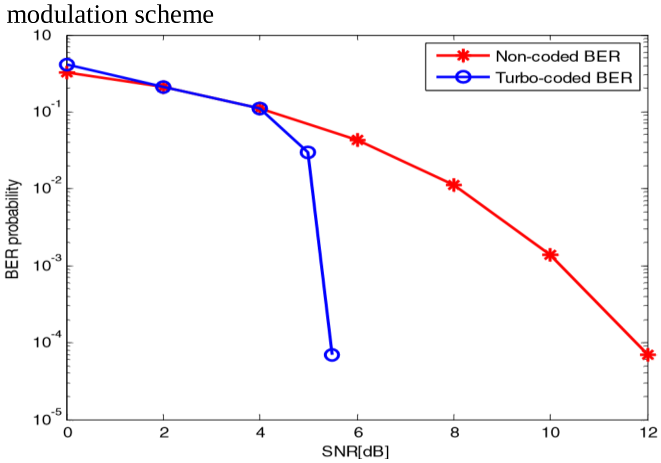

Figure.12. Non-Coded and Turbo-Channel Coded BER Performance With QPSK

Non-coded versus Turbo coded BER performance: 16-QAM

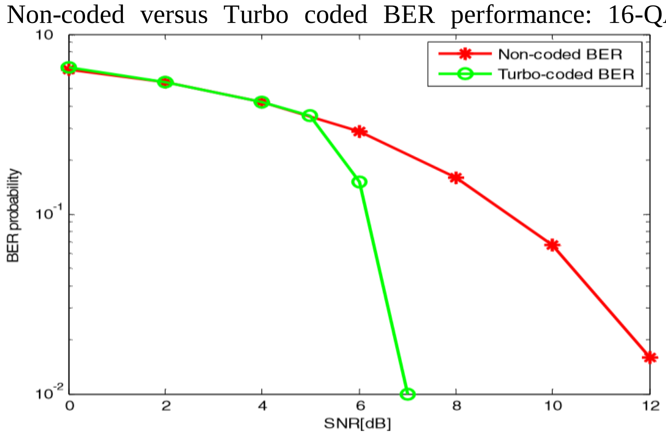

Figure.13. Non-Coded And Turbo-Channel Coded BER With 16-Qam

Non-coded versus Turbo-coded BER performance with 64-QAM

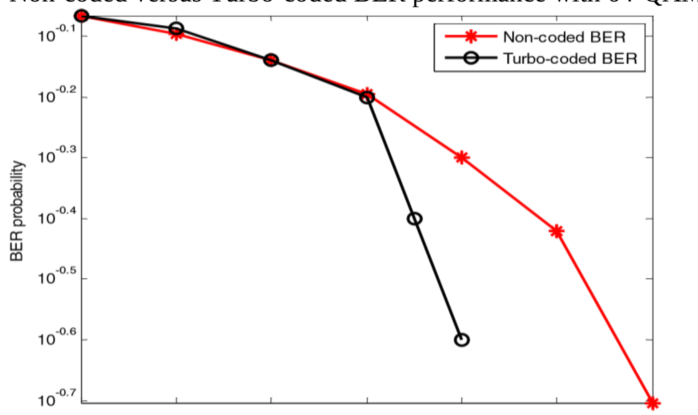

FIGURE.14. Non-Coded and Turbo-Channel Coded BER With 16-Qam

From analysis the results in FIGURE12, 13 and 14; the following observations can be drawn:

- The use of the 1/3-Turbo channel coding has considerably improved the BER performance of the LTE digital communication system in all the three modulation schemes cases.
- In all the three modulation schemes scenarios, the BER probability starts high and rapidly drops. It drops fast in the coded system than it does in the non-coded one.
- After a certain signal-to-noise ratio, the gradient(slope) of the BER of the coded LTE system becomes highly negative(almost vertical).This implies that an increase in signal's power does not affect very much the BER performance above a certain value of the SNR.
- By carefully observing the performance of the coded system in the three cases, it can clearly be seen that despite, channel coding; the reliability of the QPSK stills higher than the one of the 16-QAM and even higher than the one of the 64-QAM modulated LTE system.

VI. CONCLUSION

In this paper, the design of a LTE digital communication system in Simulink has been described. Different simulations of the designed LTE system have yield to different results. A comparison between the results obtained by simulating the LTE system without any channel coding subsystem and with the 1/3 Turbo channel coding has been established. The outcomes ofthe simulations have been analysed and it has been observed that the 1/3-Turbo channel coded LTE model performs much better in terms of BER than the non-coded model. It has also been observed that in both non-coded and 1/3 Turbo-coded scenarios, the denser the constellation modulation scheme (QPSK to 16-QAM to 64-QAM); the poorer its BER performance, meaning the poorer the reliability of the whole communication system. The benefit of our study to LTE industry and academia is to the prototyping tool and for the research and development laboratory.

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