Modem 4G LTE

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Abstract—LTE is the new mobile telecommunications system which is capable of supporting data rates which can go up to 50 Mbps in the uplink and 100 Mbps in the downlink when using a 20MHz channel bandwidth. LTE uses Orthogonal Frequency Division Multiple Access (OFDMA) for the downlink and Single Carrier Frequency Division Multiple Access (SC-FDMA) for the uplink.

The main objective of this paper is to simulate a LTE Modem both in downlink and uplink sides in order to study several parameters for evaluating its performance. In the LTE downlink the parameters analysed were the bit error rate, the number of bits transmitted per OFDM subcarrier and the number of bits transmitted per OFDM symbol. In LTE uplink the parameter analysed was the bit error rate. It was also analysed the Peak to Average Power Ratio (PAPR) both for uplink and downlink cases. The software used for the simulations was Matlab.

Index Terms—LTE, Modem, OFDM, PAPR, SC-FDMA,

I. INTRODUCTION

LTE was initiated in 2004 by NTT DoCoMo, became stable for commercial implementation in 2008 and the first public service started to be available in 2009 in Stockholm and Oslo. It is designed to support high speed data transfer and high capacity voice.

LTE uplink target is to support data rates which can go up to 50 Mbps and the LTE downlink data rates which can go up to 100 Mbps. These data rates correspond to 2.5bps/Hz and 5bps/Hz in the uplink and downlink respectively. LTE carrier frequencies are in the range 400 MHz to 4 GHz and its channel bandwidths are 1.4MHz, 3MHz, 5MHz, 10MHz, 15MHz and 20MHz. LTE has a round-trip time (RTT) less than 10ms which is especially good for real time applications like online gaming or video calls.

LTE uses Orthogonal Frequency Division Multiple Access (OFDMA) technology in the downlink and Single Carrier Frequency Division Multiple Access (SC-FDMA) in the uplink. Multiple Input Multiple Output (MIMO) technology is another innovation introduced by LTE and which consists in exploring the spatial domain using multiple antennas in the transmitter and/or in the receiver in order to improve the overall communication efficiency. LTE is a packet oriented multiservice system which as the name says is based on the packet switching principle.

II. OFDMA AND SC-FDMA

Orthogonal frequency division multiplexing (OFDM) is a multicarrier modulation scheme based on the frequency division multiplexing (FDM) concept and which consists in dividing a stream of information into several sub streams and then each of these sub streams are transmitted in parallel carried by different sub carriers. Each subcarrier may use a specific modulation scheme. The possible modulation schemes for LTE are QPSK, 16QAM and 64QAM. The sub streams have a much higher symbol time duration than the original stream (increases approximately linearly with the number of subcarriers) because they carry less information for the same period of time. The higher symbol time duration of each OFDM sub stream provides much more immunity to the inter symbol interference (ISI) caused by the multipath propagation than the original stream because the original stream is more likely that the symbol time duration is less than the channel delay spread.

The cyclic prefix consists in introducing a guard period in the beginning of each OFDM symbol. To preserve the continuity of the signal, the content of this guard period will be a copy of the information in the ending of the symbol. If the guard period is longer than the delay spread, then there will be no inter symbol interference and so the previous and the following symbols do not overlap with the current symbol.

There are two types of cyclic prefixes defined for LTE: normal cyclic prefix and the extended cyclic prefix. The time duration of the normal cyclic prefix is 4.7μs with an exception in the first OFDM symbol in the timeslot which has time duration of 5.2μs. The reason in order to have a different time duration in the cyclic prefix of the first OFDM symbol in a timeslot is due to accommodate an integer number of symbols in a timeslot. The normal cyclic prefix is used mainly in urban cells where the channel delay spread is relatively small. It is capable of handling path delay variations up to about 1.4 km. The time duration of the extended cyclic prefix is 16.7μs. The extended cyclic prefix is mainly used in rural cells or very large urban cells where the channel delay spread is higher. It is capable of providing delay spread up to 10km.

It is possible to divide a basic OFDM transmitter into several blocks where each block has a unique function. The following figure shows a possible OFDM transmitter block diagram:
The first OFDM block is the serial to parallel block which converts the bit stream into several blocks of variable number of bits and each of one will be modulated. The number of bits in each block depends on the modulation scheme used. In LTE the number of bits for each block can be two, four or six bits. The second OFDM block is called the constellation mapping which converts the blocks of bits into modulated symbols. The modulation schemes defined for LTE are QPSK, 16 QAM and 64 QAM. The criterion to choose a specific modulation scheme rather than other will depend on communication channel quality in the frequency band of the subcarrier carrying a specific modulated symbol. The third OFDM block is called the subcarrier mapping which consists in assigning the subcarriers to the modulated symbols. Each subcarrier can carry one modulated symbol each time. It is possible that some subcarriers do not carry any modulated symbol. For example LTE uses guard subcarriers each do not carry data bits. The fourth OFDM block is the N-point IFFT block which applies the Inverse Fast Fourier Transform to the modulated symbols already in the desired order. Usually the number of subcarriers carrying data is less than N. When this happens the input of the IFFT is fulfilled with zeroes in order to match the IFFT size. The fifth block is the cyclic prefix block which consists in adding samples to the N samples from the output of the IFFT. The number \( N_{CP} \) depends on the type of cyclic prefix used and on the sampling frequency. LTE cyclic prefix can have two lengths namely the normal cyclic prefix and the extended cycle prefix. The sixth block is the parallel to serial block and consists in converting the parallel samples from the output of the cyclic prefix clock into a discrete time sequence which represents the OFDM time discrete baseband signal. The seventh block is the digital to analogue (D/A) block which converts the discrete time signal into an analogue/continuous time signal. The eighth block is the P/S block which consists in converting the parallel blocks of bits into a single bit stream.

SC-FDMA is used in LTE uplink rather than OFDMA mainly due to its lower pick-to-average-ratio (PAPR) because the UE terminals have less power available for their data transmission.

It is possible to divide a basic SC-FDMA transmitter into several blocks where each block has a unique function. The following figure shows a possible SC-FDMA transmitter block diagram:
number of bits and all the blocks will be modulated using the same modulation scheme. The number of bits in all blocks depends on the modulation scheme used. In LTE the number of bits for all block can be two, four or six bits. The second SC-FDMA block is called the constellation mapping which converts the blocks of bits into modulated symbols. The modulation schemes defined for LTE are QPSK, 16 QAM and 64 QAM. As already was referred all modulated symbols will have the same modulation scheme. The criterion to choose a specific modulation scheme rather than other will depend on communication channel quality in the frequency band of the subcarrier carrying a specific modulated symbol. The third SC-FDMA block is the M-point DFT which applies the discrete Fourier transform to the modulated symbols. The operation is similar to spreading the symbols over a specific frequency band. The fourth SC-FDMA block is called the subcarrier mapping which consists in assigning the subcarriers in different ways. There are two possible ways of subcarrier mapping in SC-FDMA, localized and distributed. In localized it is allocated M adjacent subcarriers to a user. In distributed it is allocated equally spaced M subcarriers every Lth subcarrier. L must satisfy the condition ML<N. In both cases in order to match the IFFT size it is appended with zeroes the non-assigned subcarriers. The fifth SC-FDMA block is the N-point IFFT block which applies the inverse Fast Fourier Transform to the output of the subcarrier mapping samples. If M=N, then DFT and IFFT cancel each other and the modulated symbols are transmitted directly. The sixth SC-FDMA block is the cyclic prefix block which consists in adding $N_{CP}$ samples to the N samples from the output of the IFFT. The number $N_{CP}$ depends on the type of cyclic prefix used and on the sampling frequency. LTE cyclic prefix can have two lengths namely the normal cyclic prefix and the extended cycle prefix. The seventh SC-FDMA block is the parallel to serial block and consists in converting the parallel samples from the output of the cyclic prefix clock into a discrete time sequence which represents the SC-FDMA time discrete baseband signal. The seventh SC-FDMA block is the digital to analogue (D/A) block which converts the discrete time signal into an analogue/continuous time signal. The eighth SC-FDMA block is called the Radio block which basically up converts the baseband signal to a radiofrequency signal.

It is possible to divide a basic SC-FDMA receiver into several blocks where each block has a unique function. The following figure shows a possible SC-FDMA receiver block diagram:

The first block is the Radio block. This block will realize the inverse operation of the Radio block mentioned above in the OFDM transmitter above. It is basically down converts the radio signal into a continuous baseband signal. The second block is the analogue to digital (A/D) block which converts the continuous time received by the output of the radio block into a discrete time signal. The third block is the serial to parallel block and consists in converting the discrete time sequence into parallel sets of samples. The fourth block has the task of removing the $N_{CP}$ cyclic prefix samples from each of the sets of samples received from the S/P block. The fifth block is the N-point FFT block which applies the Fast Fourier Transform. The set of the FFT output samples are in the frequency domain signal. The sixth block is the subcarrier de-mapping and channel equalization block which consists in doing the inverse operation of the subcarrier mapping block and the channel equalization is supposed to compensate the amplitude and phase distortion caused by the communication channel to the signal. The seventh block is the IDFT block which has the inverse function of the DFT block of the SC-FDMA transmitter. The seventh block converts the constellation symbols into correct bits. It basically does the demodulation of each set of symbols. The eighth block is the P/S block which consists

III. LTE PHYSICAL

It is possible to divide LTE resources into three dimensions in the downlink transmission: time, frequency and space. In the time resource dimension there are defined LTE time units. The longest time unit is the LTE frame and it has an overall 10ms of time duration. This frame is constituted by 20 time slots, each one with time duration of 0.5ms. The LTE sub frame is a group of two consecutive time slots and so its time duration is 1ms. Each one of the LTE time slots contains seven OFDM symbols using the normal cyclic prefix or six time slots using the extended cyclic prefix. Each the time OFDM symbol has a time duration which is approximately equalled to 66.67 µs.

In the time-frequency grid, the smallest unit of resource is the Resource Element (RE), which consists of one subcarrier for duration of one OFDM symbol. One Resource Block consists of twelve consecutive subcarriers for duration of one slot. LTE default subcarrier spacing is 15 kHz and so a resource block occupies 180 kHz of the frequency spectrum (12x15 = 180 kHz). A resource block contains 84 REs in the case of using the normal cyclic prefix and 72 REs in the case of the using the extended cyclic prefix.

The channel bandwidths for the LTE downlink and uplink are 1.4MHz, 3MHz, 5MHz, 10MHz, 15MHz and 20MHz.

IV. MODEM

The main objective is to implement and simulate a LTE modem using the Matlab software and analyze the results in order to test theoretical aspects of the OFDM and the SC-FDMA. It will be simulated both the uplink and downlink directions. There are some important considerations that will be present in the simulations: The input bit stream of the modem is supposed to be random (bit 1 and bit 0 both with a
probability of 0.5). There will no channel coding involved. Both downlink and uplink directions will be modelled in
cbaseband. Communication channel will be modelled as a FIR
filter. The input reference signal used for channel estimation
is based on the Zadoff-chu sequence. Guarantee always a bit
error rate less than 0.001. No guard subcarriers are considered.
It will be used the normal cyclic prefix because it is assumed
we are in regular urban cell scenario. In the LTE uplink
simulation the SC-FDMA communication has DFT/IDFT
length M equal to the FFT/IFFT length N. The modulation
scheme choice for each subcarrier or for all the subcarriers is
based on the bit loading formulas. The chosen numbers of
subcarriers for simulation were 512, 1024 and 2048. These
numbers were chosen due to the fact they differ from each
other by a factor of 2 which allows observing more easily
variations in the parameters with the number of subcarriers.
The OFDM transmitter and the OFDM receiver must be
modelled as well as the communication channel between
them. The goal is to study the performance of the modem
guaranteeing always an error bit probability less than 0.001.

To maximize the OFDM transmission (send the maximum bits
guaranteeing the bit error rate less than 0.001), it is useful to
use a formula which gives the best modulation technique for
each subcarrier for a specific bit error rate (modified Shannon
formula).

Now it will be describe the sequence of the procedures used
the Modem for downlink. First it will be generated a random
bit stream with a sufficient large number of bits in order to
have more accurate results. Then the bit stream will be divided
into sub streams, each of them carried by a specific OFDM
subcarrier. Each OFDM subcarrier will have different
modulation techniques according to each of the subcarrier
channel quality. For example if a specific channel has a
Channel Quality Index (CQI) 8, then the modulation scheme
chosen for this channel will be 16 QAM according to the CQI
table for LTE. The CQI index depends mainly on the Signal to
Noise Ratio (SNR.) The modulated symbols will enter in the
IFFT processing and from the output samples from the IFFT it
will be added the cyclic prefix samples. This baseband OFDM
signal enters the communication channel.

The OFDM receiver like the OFDM transmitter will be
modelled in almost the reverse way. First it will be removed
the cyclic prefix samples from the signal. After that the
remaining samples will enter in the FFT processing. The
channel equalization is done dividing the FFT output samples
by the channel transfer function in the frequency domain (this
procedure almost eliminates the distortion caused by the
communication channel because the communication channel
noise it is impossible to predict). The output of the FFT
processing after the channel equalization will be the
modulated symbols (constellation). To correctly demodulate
each subcarrier, the receiver needs to previously know all the
modulation schemes used for each subcarrier. Finally, the
original bit stream is compared with de demodulated bit
stream and it is obtained the error bits. The bit error rate is
obtained dividing the number of error bits by the number of all
the transmitted bits.

V. DOWNLINK SIMULATIONS PART 1

In the downlink simulations, the OFDM signal analyzed is not
the practical implementation of the LTE downlink mainly
because in these simulations each of OFDM subcarriers can
have different modulation schemes from each other. In the
practical implementation of LTE downlink, the resources are
grouped into resource blocks as already. Each of these
resource blocks contains twelve OFDM subcarriers, all using
the same modulation scheme. The purpose of these downlink
simulations is to study a general OFDM signal in an outdoor
environment.

The main objective is to compare the frequency response of
the FIR filter used to simulate the communication channel and
the number of bits transmitted per each OFDM subcarrier. It is
expected that the OFDM subcarriers in the frequency zones
that suffer more attenuation by the communication channel,
transmit less number of bits per modulated symbol and the
OFDM subcarriers in the frequency zones that suffer less
attenuation by the communication channel, transmit more
number of bits per modulated symbol. The number of bits per
modulated symbols can have the values 2, 4 and 6
(corresponding to the modulation schemes QPSK, 16QAM
and 64 QAM respectively) but also the 0 value in the case of
no modulation scheme used which is the same of saying that
no bits are transmitted in that OFDM subcarrier because of the
very high attenuation of the communication channel in that
frequency zone.

![Figure 5 - Number of bits/symbols transmitted per subcarrier for the case of 512 subcarriers with a Signal to Noise Ratio of 27.7 dB](image-url)
frequency zones in the FIR filter frequency response graphic with less attenuation have more transmitted bits per modulated symbol on the three cases (512, 1024 and 2048 OFDM subcarriers). The last statement can be proved looking in the little zone at the lowest frequency band where the FIR filter magnitude can be considered high and then observing the corresponding frequency zone in the figures 5, 6 and 7, it is can be concluded that all the OFDM subcarriers belonging to that zone use 64QAM which correspond to 6 bits per modulation symbol, the maximum value. Following the same logic it can be concluded looking at the FIR filter frequency response graphic that in the frequency zones with more attenuation correspond that less transmitted bits per modulated symbols or even no transmission when the attenuation is very high for the 5, 6 and 7 figures.

The main objective is to measure the variation of the number of bits transmitted per OFDM symbol with the global Signal to Noise Ratio. This global Signal to Noise Ratio is obtained by calculating the mean Signal to Noise Ration all the OFDM symbols. It is expected that the number of bits transmitted per OFDM symbol increase with the increase of the global Signal to Noise Ratio because the bigger the Signal to Noise Ration is, more bits per OFDM symbol is possible to transmit according to the Shannon formula already explained for each OFDM subcarrier. The number of bits transmitted per OFDM symbol is the sum of all the bits transmitted per OFDM subcarrier.

These two graphics confirm the theoretical expectations in the way that the OFDM subcarriers corresponding to the
As expected the number of bits transmitted per OFDM symbol increase with the Signal to Noise Ratio for the three cases (512, 1024 and 2048 subcarriers). It can be concluded from the simulations that the number of bits transmitted per OFDM symbol has an approximately linear dependence with the number of OFDM subcarriers which is the same of saying that for the same Signal to Noise Ratio, the number, the number of bits transmitted per OFDM symbol doubles when the number of OFDM subcarriers doubles for example.

The objective is to measure the variation of the bit error rate with the global Signal to Noise Ratio. It was expected that the bit error rate decrease with the increase of the Signal to Noise Ratio if there was no variation of the modulation schemes for all the OFDM subcarriers. The behaviour of the downlink simulation is: when there is sufficient Signal to Noise Ratio to guarantee a bit error rate less than 0.001 for a higher order modulation scheme for a particular OFDM subcarrier, the modulation changes. Every time an OFDM subcarrier changes to a higher order modulation scheme for the same Signal to Noise Ratio, the bit error rate increases. There are cases when the global Signal to Noise Ratio increases, some OFDM subcarriers changes to higher order modulation schemes and so these subcarriers contribute to a higher bit error rate and the remaining subcarriers contribute to a lower bit rate because the Signal to Noise Ratio increased. Thus it is very hard to predict an accurate behaviour of the bit error rate although it is possible to say that from a certain high value of Signal to Noise Ratio the bit error rate always decreases because when it is achieved the highest order modulation scheme (64 QAM), if the Signal to Noise Ration increases the bit error rate will decrease.

The bit error rate will be always less than 0.001 and if it is not possible to guarantee this bit error rate there will be no transmission.

By observing the three graphics it can be concluded that the bit error rate decreases when the Signal to Noise Ratio increases except in a little zone. The bit error rate value is also has expected never more than 0.001 for all Signals to Noise Ratio values. If the simulations were done with a very low Signal to Noise Ratio there was no transmission because it would not be possible to guarantee a bit error rate less than 0.001.
VI. DOWNLINK SIMULATIONS PART 2

The downlink part 2 simulations’ main difference with the downlink part 1 lies in the fact that the downlink part 2 assigns to each user a specific number of resource blocks instead of transmitting the data in the entire bandwidth like in the downlink part 1. All the OFDM subcarriers of the resource blocks belonging to the same user will have the same modulation scheme. The modulation scheme used for the resource blocks belonging to a specific user will consist in calculating the error bit probability for each subcarrier, adding all the values and then diving by the number of subcarriers. The result gives the overall bit error probability.

The main objective is to measure the variation of the bit error rate with the Signal to Noise Ratio in scenario in a case where it is supposed to simulate an OFDMA application where only one user is receiving information. It is expected that the bit error rate decrease with the increase of the Signal to Noise Ratio for the same modulation scheme. When the modem changes to a higher order modulation scheme the bit error rate increases but always below of the 0.001 limit. In summary, the global expected behaviour is: from the point when there is sufficient Signal to Noise Ratio to transmit with the lowest order modulation scheme (QPSK) until it changes to 16 QAM, the bit error rate decreases. Immediately when the modulation scheme changes the bit error rate increases to a value near the 0.001 limit. Then until the modulation scheme changes again (16 QAM to 64 QAM in this case) the bit error rate will decrease again. Again in the moment when the modulation scheme is changed to 64QAM the bit error rate increases to a value near the 0.001 limit. From this point the bit error rate will decrease infinitely with the Signal to Noise Ratio because there will be no more modulation scheme changes.

As expected the bit error rate decreases with the Signal to Noise Ratio for the same modulation scheme. The only bit error rate growth zone is when the modem changes to a higher order modulation scheme.

VII. UPLINK SIMULATIONS

The main objective is to measure the variation of the bit error rate with the Signal to Noise Ratio and also the variation of the modulation scheme used with the Signal to Noise Ratio. It is expected, like in the downlink that the bit error rate decreases with the increase of the Signal to Noise Ratio. The objective is also to compare the behavior of the graphic with the downlink’s simulations.
The two graphics above show that for a specific modulation scheme in the SC-FDMA, the bit error rate decreases with the Signal to Noise Ratio. This fact is due to the fact that the Modem is simulated in order to achieve a bit error rate less than 0.001 and so when a specific Signal to Noise Ratio is enough to achieve a bit error rate less than 0.001, the Modem can use a better modulation scheme. When the Signal to Noise Ratio is too low it is impossible to transmit information because there is no modulation scheme available to achieve a bit error rate less than 0.001.

VIII. UPLINK VS DOW NLINK SIMULATIONS

The Pick-to-Average-Ratio (PAPR) is obtained dividing the maximum value by the mean of the samples of the OFDM/SC-FDMA signals before passing in the communication channel. The main objective is to study the Pick-to-Average-Ratio (PAPR) for different number of subcarriers either for OFDM and SC-FDMA.

It is clear that for all the situations analysed an OFDM signal has always a higher PAPR than a SC-FDMA signal. The statement confirm the theoretical

In the case of SC-FDMA, as expected, the PAPR stays stable with different number of subcarriers.

In the case of OFDM, the PAPR grows with the increase of the number of OFDM subcarriers. It can be explained because the higher the value of the peak in the OFDM signal is, higher is achieved when there are higher number of subcarriers contributing constructively.

IX. CONCLUSION

Although the real LTE downlink and uplink transmissions procedures are far more complex than the ones used in the simulations, the objective was to retract as close as possible as to the reality both uplink and downlink of LTE.

In the downlink simulations part 1 (OFDM simulations) the main conclusions to take are the following: OFDM subcarriers which suffer more attenuation by the communication channel carry less bits; Although the behaviour is not completely linear, it can be stated that the higher the SNR is, the greater number of bits is transmitted per OFDM symbol; The bit error rate decreases for almost the simulations with the SNR.

In the downlink simulations part 2 (OFDMA simulations) the main conclusions are: For the same modulation scheme the bit error rate decreases with SNR; There are some switch behaviour of the bit error rate when a higher order modulation scheme is used increasing the bit error rate in that precise point. In the uplink simulations (SC-FDMA simulations) the main conclusions to take are: The behaviour of the bit error rate is similar to the OFDMA simulations but in this case there is a need of guaranteeing a higher SNR to achieve the same bit error rate. In the downlink vs uplink (PAPR simulations) the main conclusions are: PAPR is always higher in LTE uplink (SC-FDMA) than in LTE downlink (OFDM) for all the cases analysed. The higher number of OFDM subcarriers, the greater the value of PAPR is; The PAPR value doesn’t change with SC-FDMA subcarriers variation.
REFERENCES


