LTE Uplink Transmission Scheme

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Abstract—**The Long Term Evolution (LTE) standard requires an uplink transmission rate of up to 86 Mbps. In order to support such a high data rate and avoid the high Peak-to-Average Power Ratio (PAPR) disadvantage in Orthogonal-FDMA, Single Carrier Frequency Division Multiple Access(SC-FDMA) is used in the uplink communication in LTE cellular systems. In this paper an overview of LTE and the LTE uplink transmissions is given, especially the SC-FDMA technique. Additionally results from a PAPR analysis, comparing OFDMA and SC-FDMA using different subcarrier mapping schemes, are presented. Finally an adaptive hybrid subcarrier mapping scheme, a combination of localized and distributed mapping schemes, is proposed as a technique for reaching good transmission performance with low PAPR.**

Index Terms—**SC-FDMA, PAPR, LTE, Long Term Evolution, Uplink Transmission, LTE Uplink**

I. INTRODUCTION

The demands on mobile communication networks have never been higher. The introduction of smart phones, almost constant access to wireless networks for laptops and an increase of mobile broadband for laptops have had a major impact on our habit of having constant access to the Internet. Applications such as streaming music and HD-video that take advantage of this and a steady increase of the number of subscribers that are using these services are pushing the requirements for high speed mobile broadband technologies even higher. It is clear that the 3G mobile networks with peak speeds of a few Mbits/s will not be sufficient. Updates such as High Speed Packet Access (HSPA) increase the speeds but the requirement of being backwards compatible incur limits of how high the performance can be pushed. [2]

The 3rd Generation Partnership Program (3GPP) leads the specification of the next radio access technology that should take the telecom industry into the 2020s, known as Long-Term Evolution (LTE). LTE is not required to be compatible with old technologies which relieves it from some of the restrictions that are put on HSPA. Even if this allows LTE to be designed completely from scratch many good techniques from the 3G-networks are being reused in LTE. There are of course also a number of new techniques in order to achieve maximum performance. One of the basic changes is that LTE is designed to optimize IP based communication since there is no need for circuit-switched services. Some of the requirements placed on LTE are that it should be more flexible in the utilization of the frequency spectrum and it should not only have higher data rates and lower latencies, but the data rates and latencies should also be high at the cell edges. [2]

To support these requirements the transmission schemes for the uplink (user equipment to base station) and the downlink (base station to user equipment) includes new solutions compared to the 3G networks. The aim of this article is to describe the uplink transmission scheme of LTE, specifically the multiple access technique known as Single-Carrier Frequency Division Multiple Access (SC-FDMA) and also to present techniques that could improve the performance additionally.

The remaining of the article is organized as follows. Section II gives a brief overview of LTE and mobile networks. Section III provides a more detailed overview of the uplink transmission scheme in LTE. Section IV presents the frame structure of the LTE radio interface. In section V SC-FDMA is explained at a more detailed level, issues related to frequency mapping schemes are also presented as well as a peak-to-average power ratio (PAPR) analysis. Section VI proposes an adaptive hybrid subcarrier mapping scheme based on channel dependent scheduling. The article is concluded in section VII which highlights the main points made in the article.

II. OVERVIEW OF LTE

Networks for mobile communication are typically divided into a Radio Access Network (RAN) and a Core Network. The RAN handles functionality related to the physical and link layers such as coding, interleaving, modulation, header compression etc. It may also handle security functions, ciphering for example, and functions related to managing the radio resources. The core network handles for example subscriber information, data policy control and interconnection to external networks. The work with the specification of the core network in LTE is called System Architecture Evolution (SAE). Important design philosophies for LTE were to have a RAN with only one type of node, called the eNodeB, and a core network that as far as possible is independent of the radio access technology used, the later in order to let the core network be able to use legacy systems and other technologies such as Wimax.

The design targets of LTE is to provide a peak data rate of at least 100 Mbps in the downlink and 50 Mbps in the uplink when operating in a bandwidth of 20 MHz. This could also be specified as 5 bit/s/Hz and 2.5 bit/s/Hz respectively. The maximal performance should be available when a terminal is stationary or moving at a low speed of up to 15 km/h. For speeds up to 120 km/h a slight degradation is allowed but the system should be able to manage terminals with speeds up to 350 km/h or even 500 km/h for some frequency bands. The coverage requirements in an environment with no interference are to meet the other requirements in cells with a range of five kilometers. For up to 30 kilometers some degradation is acceptable and ranges up to 100 km should not be precluded [2]. However, simulations show that the theoretical peak data rates of LTE are more than 325 Mbps in downlink and more than 80 Mbps in uplink. [5]

Additionally, LTE should support both Frequency- and Time-Division-Duplex (FDD, TDD), meaning that in FDD different frequency bands are used for the downlink and uplink while in TDD downlink and uplink transmissions use the same frequency band but are done in separate time slots. [2]

To fulfill all the requirements LTE uses a transmission scheme called Orthogonal Frequency Division Multiplexing (OFDM) for the downlink and SC-FDMA for the uplink. SC-FMDA will be described in more detail in the following sections.

III. OVERVIEW OF LTE UPLINK TRANSMISSION

The high data rates of the LTE standard does not only need wider bandwidth but also a more advanced modulation technique. While Orthogonal Frequency Divsion Multiplexing (OFDM) is considered to be the optimum modulation technique to fulfill the downlink transmission requirement, the high Peak-to-Average Power Ratio (PAPR) property of OFDM makes it less favorable for the uplink transmission. Instead, the Single-Carrier FDMA technique is used. This technique is also known as DFT-Spread OFDM (DFTS-OFDM) where DFT is an acronym for Discrete Fourier Transform.

The SC-FDM modulation is quite similar to the OFDM except that before the Inverse DFT (IDFT) in transmission side of OFDM, an extra DFT processing is added in the DFTS-OFDM and vice versa after the DFT in OFDM receiver side. That is also where the DFTS-OFDM gets its name. The extended transformations make the information of each information bit spread over all the subcarriers, which results in significantly smaller variations in the instantaneous power of the transmitted signal, which is usually enjoyed by 'single-carrier' transmission schemes. The similarities with these techniques are the reason for the name of SC-FDMA. Fig. 1 displays a comparison between OFDM and SC-FDMA and shows how each symbol is spread to multiple subcarriers instead of beeing transmitted over one subcarrier.

In addition to the low-PAPR ('single-carrier' property) inherent in SC-FDMA, it also has some other desired properties for a transmission scheme. SC-FDMA allows for the possibility for low-complexity but high-quality equalization in the frequency domain and it is also possible to have flexible bandwidth assignments with SC-FDMA. [2]

Another benefit of SC-FDMA is the so-called ”built-in” frequency diversity. Because SC-FDMA spread the information of one symbol through all the available subcarriers, so in case losing partial information on one (or even more) subcarriers due to deep fading does not necessarily lead to losing the information modulated in the symbol. [1]

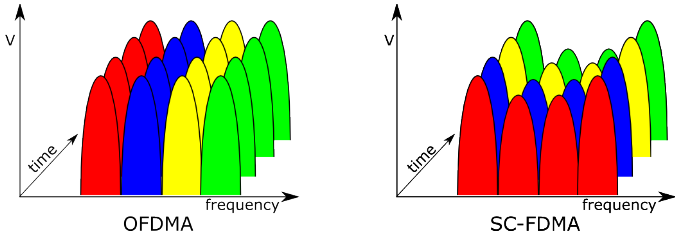

Fig. 1. Comparison between OFDMA and SC-FDMA

IV. LTE UPLINK FRAME AND SUBFRAME

In order to transfer data between LTE base station called eNodeB and User Equipement terminals, a strict frame and sub-frame (slots) structure has been defined for the radio interface E-UTRA (Evolved UMTS Terrestrial Radio Access) used in LTE. Two general frame types are distinguished:

- Type 1 - used in both LTE FDD and TDD duplexing
- Type 2 - used only in LTE TDD duplexing

Due to more frequent use [10], in this paper mainly Type 1 will be investigated.

1) Type 1 frames: The generic LTE frame has a duration of 10 msec. It is divided into ten subframes also known as TTI (Transmission Time Interval) [7]. Each subframe duration is $T_{subframe} = 1.0$ msec and it consists of two time slots. As is it shown in Fig. 2 each frame can also be considered as a structure divided into 20 separate time slots each with a duration of 0.5 msec.

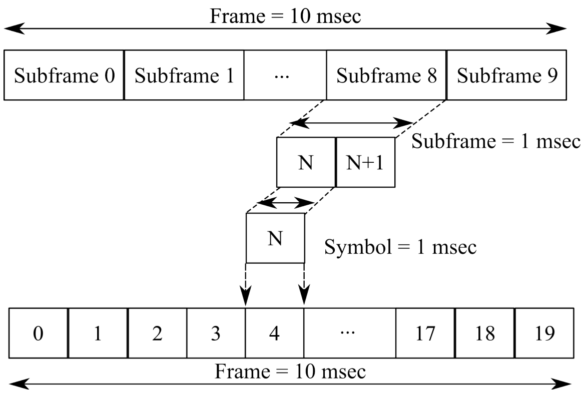

Fig. 2. Uplink frame and subframe format for structure type 1

The number of symbols (consider one symbol as DFT blocks + cyclic prefix (CP)) in one slot is determined by CP length [9]. When normal CP is used there are seven SC-FDMA symbols per slot, but for extended CP only six symbols can be transmitted. This is illustrated in Fig. 3.

Comparing the TTI in LTE with the subframes in HSPA systems the LTE subframe is two times shorter than the subframe in HSPA which has a duration of 2 msec. The main objective of the LTE subframes structure is to provide higher

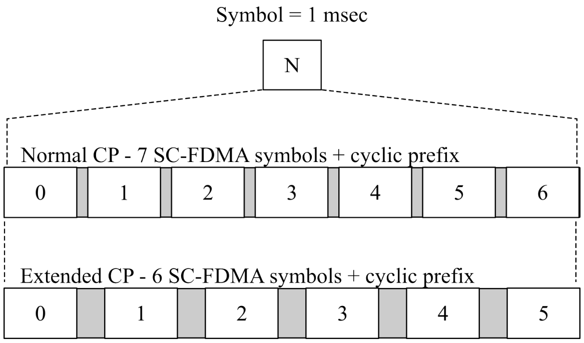

Fig. 3. Symbol structure consisting of seven or six modulation symbols depending on the cycle prefix length

data rates and smaller latency. This is achieved inter alia using a shorter LTE subframes duration so e.g delays caused by retransmissions are reduced.

2) Type 2 frames: Type 2 frames are used in LTE-Time Division Duplexing systems only. The same frame structure is used both in uplink and downlink. The difference is that main frame is divided into two half-frames, each of five milliseconds. One half-frame is then built up of five subframes of $T_{subframe} = 1.0msec$ each.

One of the main advantages of using LTE-TDD systems is the ability to dynamically change bandwidth for uplink and downlink, depending on current needs, network load etc.

V. SC-FDMA IN LTE UPLINK

A. SC-FDMA System Configuration

Fig 4 shows the block diagrams of SC-FDMA transmitter and receiver. This diagram is similar to the block diagram of OFDMA except with two yellow blocks. SC-FDMA transmitter will convert binary data into a sequence of modulated subcarriers which is to be transmitted through the radio channel. To do so many signal process operations are required.

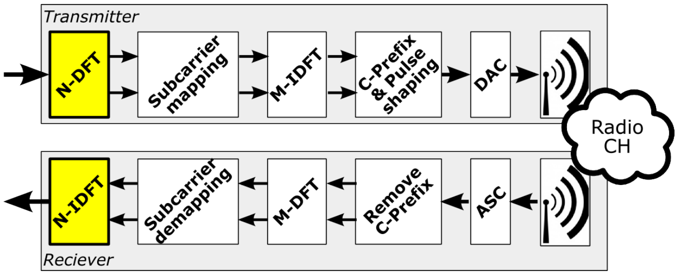

Fig. 4. Block Diagram of the transmitter and receiver of SC-FDMA

First the data symbols are modulated by a base band modulator to form a sequence of modulated complex symbols. LTE is using an adaptive base band modulation scheme so depending upon the channel it will adopt the modulation formats. The common modulation being used in LTE are Quadrature Phase Shift keying (QPSK), Binary Phase shift Keying (BPSK), 16 level quadrature amplitude modulation (16-QAM) and 64-QAM. The next step is to convert the serial modulated data into N parallel data streams or group the data into a blocks of N modulated symbols. Then it performs an N point Discrete Fourier Transform (DFT), this step will transform time domain modulated symbols to frequency domain symbols.

The next step is sub-carrier mapping which maps N DFT output symbols to one of M orthogonal sub-carriers. M is the number of orthogonal frequency sub-carriers, which is greater than N, and N should be an integer multiple of M so that M=N*Q where Q is the bandwidth expansion factor or maximum number of users that can be supported by a system. As an example, if N=64 and M=256 then Q=4 so the maximum number of user that can be supported by the system simultaneously are four. The result of sub-carrier mapping is that we have a set of complex symbols. After this, just like in OFDM, a Inverse DFT (IDFT) is performed which transforms complex frequency domain symbols to time domain signal. Then each symbol is modulated by a single high frequency carrier and transmitted sequentially. If M=N then we can skip the DFT, frequency Mapping and IDFT blocks [6] and direct modulated our time domain complex symbols to a single frequency.

After that the Cyclic Prefix (CP) will be added. The CP means prefixing symbols with a copy of the end of the symbol. The CP has two purposes here, the first is that it is use as a guard interval to eliminate the Inter Symbol Interference (ISI) (Symbol refer to OFDMA Symbol) from the previous symbol. The second is that prefixing the symbols with repetition of the end makes symbol periodic and linear convolution with channel will changes to circular convolution [4]. In frequency domain its equivalent to point-wise multiplication of symbols to channel frequency response. To ease equalization, the length of CP should be minimum equal to maximum delay in the channel or in other words equal to the delay spread of the channel [6]. Before modulating the signal with high frequency to transmit there is a pulse shaping filter that will shape the signal to get the desired spectrum.

At the receiver side we will do exactly the inverse of what we have done at transmitter. First we demodulate our signal to a lower frequency we sampled it for digital processing we will remove CP since CP is an overhead it should be as optimized as possible. After removing the CP the receiver transform the received signal into frequency domain with the help of DFT. It then de-maps the sub-carriers and then perform frequency domain equalization. Normally the most common equalizer used is minimum mean square error (MMSE) frequency domain equalizer. The equalized signal is then transformed to time domain by IDFT and detection is done in time domain [8].

B. Frequency mapping schemes

The performance of SC-FDMA system is highly affected by the type of mapping scheme that is being used. There are two main types of mapping schemes that a SC-FDMA system can adopt, one is distributed and the other is localized.

1) Localized Scheme: In a localized scheme each user use a set of adjacent subcarriers to transmit its data. This means for localized SC-FDMA (LFDMA) only a fraction of the total bandwidth is used by one user, this scheme is shown in Fig. 5. The advantage of LFDMA is that it achieve multi user diversity in frequency selective channel if each user is assigned subcarriers that have high channel gain. The disadvantage of this scheme is that it eliminate the chance of getting frequency diversity in the channel. It also requires channel state information (CSI) to map the data into the best adjacent symbols [11].

2) Distributed Scheme: In a distributed scheme the subcarriers used by a user are spread over the entire bandwidth. Since the information is spread it provides inherent frequency diversity. One of the common versions of distributed schemes is Interleaved SC-FDMA (IFDMA) in which the subcarriers that are assigned to terminals are equal distant to each other. The disadvantage of this scheme is that we are losing user diversity.

Fig. 5 shows the LFDMA and DFDMA schemes. In this figure Q=3 so it can support three users simultaneously. The total number of subcarriers M is 12 and subcarriers per user N=4. In Localized scheme terminal one used four adjacent subcarriers from 1 to 4, terminal two used subcarriers 5 to 8. In DFDMA terminal 1 can use any 4 subcarriers between 1 to 12 but in this example it is using sub-carriers 1, 4, 7 and 12.

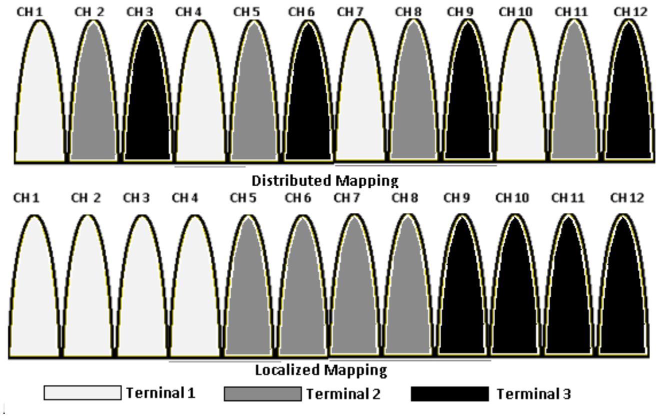

Fig. 5. Distributed and Localized sub-carrier mapping

C. SC-FDMA Peak-to-Average Power Ratio Analysis

One of the fundamental performance measurement of transmitter power efficiency is Peak-to-Average Power Ratio (PAPR). The PAPR is calculated as a ratio of peak power amplitude to root mean square (RMS) power value of the transmitted signal in particular transmission block [8]:

$$PAPR = \frac{|X|_{peak}}{X_{RMS}}$$

Peak-to-Average Power Ratio for SC-FDMA modulation, according to [12], could not be easily obtained analytically. In this paper we rely on a numerical analysis based on simulations presented in [8]. The simulations were aimed to observe the differences in PAPR between OFDMA systems and different frequency mapping schemes in SC-FDMA localized (LFDMA) and distributed (in this case only interleaved IFDMA mapping scheme was considered).

Data in Fig. 6 - 9 is presented as complementary cumulative distribution function (CCDF), which is the probability that PAPR is higher than a $PAPR$ value $PAPR_0$. Marked on y axis on Figures as ($Pr\{PAPR > PAPR_0\}$) and defined as

$$F_c(x) = P(X > x) = 1 - F(x)$$

We simulated a system with 512 subcarriers in transmission bandwidth $B = 5MHz$, data block size was set to $N = 16$. Spreading factor defined as Q=M/N = 512/16=32. For each block to calculate PAPR value, when using pulse shaping value is oversampled four times. When considering OFDMA system simulations no pulse shaping is used.

According to [3] the raised cosine impulse response is:

$$h(t) = \frac{sinc(\frac{t}{T})cos(\frac{\pi\alpha t}{T})}{1 - 4\left(\frac{\alpha t}{T}\right)^2}$$

where α is a constant $0 < \alpha < 1$ also known as the roll-off factor. Alpha defines the width of the middle frequencies. The lower the α value the greater attenuation of out-of-band signal components and the more pulse shaping is introduced. In our simulations we set the value $\alpha = 0.1$.

In Figures 6 - 9 we present the comparison between PAPR of SC-FDMA(IFDMA and LFDMA) and OFDMA systems. Figures 6 and 7 present results of simulation when Q-PSK modulation is used and in the figures 8 and 9 16-QAM is considered, both with and without pulse shaping. After comparing all figures it could be easily seen that indeed OFDMA signals have much higher PAPR than SC-FDMA signals. When considering systems without pulse shaping (see Fig. 7 and Fig. 9) the LFDMA has lower PAPR than OFDMA by about 2.5dB for QPSK and more than 1.5dB for 16-QAM modulation. The biggest differences were revealed between OFDMA and IFDMA and they are more than 10dB when using QPSK and over 5dB for 16-QAM. But it has to be said that these values were achieved in systems without pulse shaping, which makes them more theoretical than practically usable.

After observing Fig. 6 and Fig. 8 several conclusions could be drawn. First of all, after applying raised-cosine pulse shaping PAPR values for both IFDMA and LFDMA decreased. Moreover pulse shaping seems to be more harmful for IFDMA PAPR values than for LFDMA. Comparing PAPR values for IFDMA using Q-PSK between Fig. 6 (with pulse shaping) and Fig. 7 (without pulse shaping) it could be seen that the difference between these values is about 7dB. For 16-QAM it is about 3.5dB. In contrast difference for LFDMA with and without pulse shaping is much less significant and varies from 0.2dB for Q-PSK to about 0.5dB when 16-QAM is used.

In conclusion, SC-FDMA have indeed lower PAPR than OFDMA in general. Also, using raised-cosine pulse shaping is decreasing PAPR the most significant when using IFDMA frequency mapping scheme and Q-PSK modulation, which has

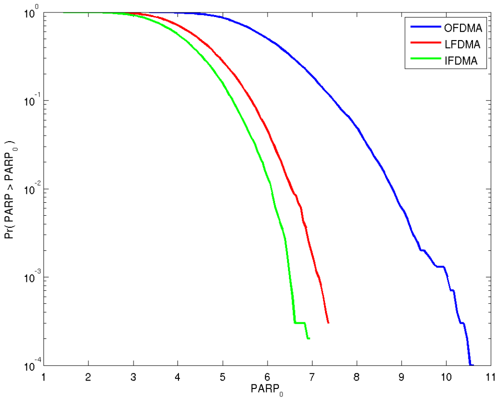

Fig. 6. PAPR analysis comparison OFDMA, LFDMA and IFDMA: M=512 N=16 α=0.1 with cosine pulse shaping using Q-PSK

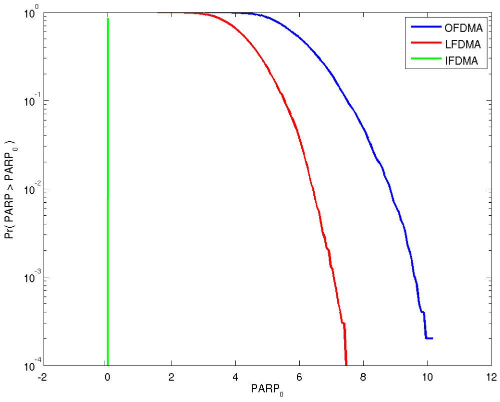

Fig. 7. PAPR analysis comparison OFDMA, LFDMA and IFDMA: M=512 N=16 without pulse shaping using Q-PSK

the lowest PAPR (over 10dB difference compared to OFDMA) when no pulse shaping is used.

VI. PROPOSED IMPROVEMENT

A. *Adaptive Hybrid Mapping*

The above discussion gives a view of advantages and disadvantages of different sub-carrier schemes. If we adopt Localized subcarrier mapping then we are losing frequency diversity, and if we adopt Distributed mapping then we are losing multi-user diversity. Also since LTE is using adaptive modulation it have CSI (channel state information), but these mapping schemes are not using CSI efficiently. To overcome this difficulty researchers are thinking about different sub-carrier mapping scheme that is optimal in the sense that it maximizes the advantages of both schemes and minimizes the disadvantages of these scheme.

One way to overcome this difficulty is to use an adaptive sub-carrier scheme. The idea behind this scheme is to use the CSI and depending upon certain performance criteria adopt different subcarrier mapping schemes. As an explanation at transmitter side we will send pilot signals to estimate each channel, this estimation is called CSIT (channel state information at transmitter). For a sake of simplicity we have set a criteria to search if the number of consecutive sub-carriers are greater than half of the total sub-carriers per user (N/2). If this criteria is met it will go for localized scheme else it will go for distributed scheme.

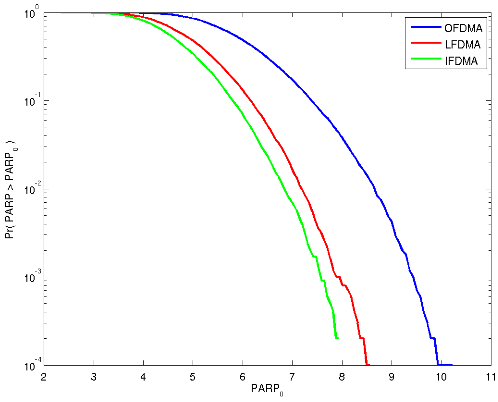

Fig. 8. PAPR analysis comparison OFDMA, LFDMA and IFDMA: M=512 N=16 α=0.1 with cosine pulse shaping using 16-QAM

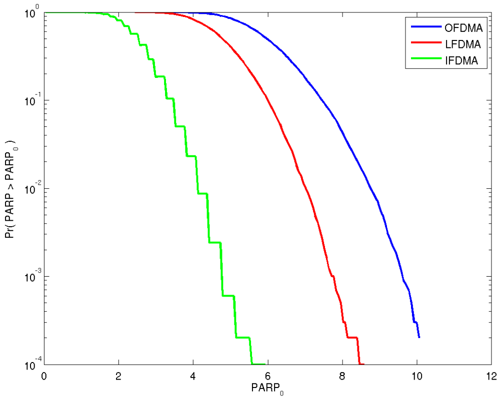

Fig. 9. PAPR analysis comparison OFDMA, LFDMA and IFDMA: M=512 N=16, without pulse shaping using 16-QAM

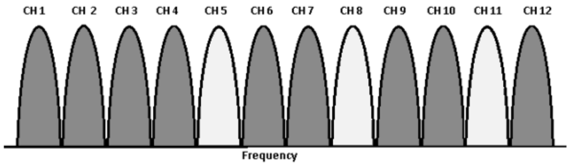

Fig. 10. Adaptive mapping scheme (Localized)

Fig.10 shows the example of such a scheme. In this example we have M=12 (total number of sub-carriers) N=3 (sub-carrier per user) this mean that this system can support at most 12/3=4 users at a time. The dark gray color indicates good channels and light gray color indicates carriers in deep fade or simply bad channels. By analyzing the CSIT at transmitter we found three consecutive sub-carriers in good condition so we will adopt localized scheme and gain multi-user diversity.

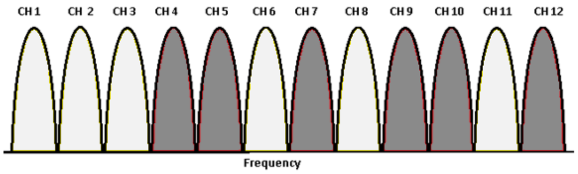

Fig. 11. Adaptive mapping scheme (Distributed)

The above figure shows another CSIT. Now again the system searches for two (N/2) or greater then two consecutive good sub-carriers. Now it failed to found two or more good consecutive channels so it will go for Distributed scheme and gain frequency diversity, also it reduces BER (bit error rate). For example if we had used the localized scheme for such a channel and assigned first four sub-carriers to user one then three out of four sub-carriers are in deep fade which means that terminal one may lose three constitutive symbols. To correct this we have to use very strong error correcting code that reduce spectral as well as power efficiency. But now by doing distributed scheme and assigning CH 1, CH 3, CH 7 and CH 10 to user 1 only one sub-carrier will be in fade and if a symbol is lost due to this fade then it can be easily corrected by cheep error correcting codes.

One of the drawbacks of this scheme is that it will increase the complexity since for distributed mapping scheme frequency synchronization at receiver is a big problem. This problem can be overcome by using interleaved frequency division multiple access (IFDMA) which is a special case of distributed mapping. In this way we are permanently assigning certain sub-carriers to eacch terminal. For example if the system decided to use IFDMA then terminal one will always occupy ch 1,4,7 and 10 and the receiver know that ch 1, 4, 7 and 10 are for terminal one only. So as a synchronization information transmitter only need to send the receiver which mapping scheme it is using. For example if transmitter says that it is now using IFDMA then receiver knows that sub-carrier 1, 4, 7 and 10 are for terminal one and if it says that it is using LFDMA then receiver know that ch 1 2 3 and 4 are for terminal one.

The Fig.12 shows the expected PAPR characteristic of adaptive mapping under different probability of adaption. Initially we suppose that our system is using localized mapping, then we change our subcarrier mapping to interleaved in different percentage. We see that in any case the Adaptive PAPR curve lies between IFDMA and LFDMA. Of course in adaptive scheme we are sacrificing up to some extent in terms of user and frequency diversity.

VII. CONCLUSIONS

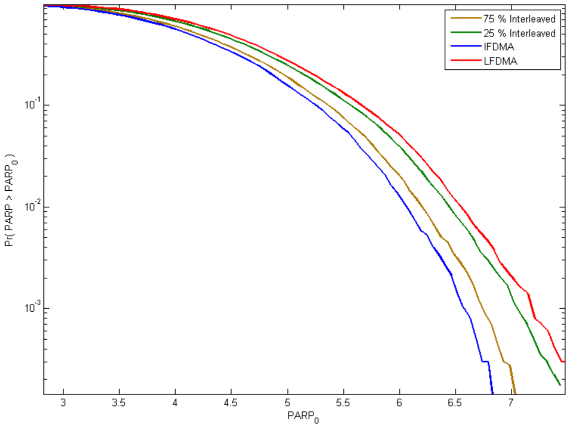

Fig. 12. PAPR of Adaptive mapping

SC-FDMA is the new multiple access technique adopted in the LTE uplink transmission scheme. Compared with the popular OFDMA, which is used in the LTE downlink transmission and WiMAX, SC-FDMA has a better performance in terms of PAPR and Frame Error Rate (FER) due to its coherent 'single-carrier' property and built-in frequency diversity.

In this paper, we have given an overview of LTE and LTE uplink transmission. The advanced technology behind the uplink transmission: SC-FDMA is analysed specifically. A comparison between the OFDMA and SC-FDMA is also done, which shows that SC-FDMA has a much lower PAPR than OFDMA. And different subcarrier mapping schemes will also result in different PAPRs. IFDMA has a slightly better performance in terms of PAPR than LFDMA. In the end, an Adaptive Hybrid Mapping scheme is proposed, which combines the advantages of both localized and distributed schemes.

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