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Physical Layer Aspects of 3GPP's Long Term Evolution (LTE)

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Abstract --LTE is specified by the 3rd generation partnership project as a standard for high speed data transfer in 4th generation wireless communication networks. This paper provides an in depth over view of the generic frame structure of physical layer of LTE for both uplink and downlink together with advance techniques which are new to cellular systems such as OFDM, OFDMA and MIMO along with their advantages over traditional techniques. It also summarizes the modulation parameters used in the uplink and downlink of 3GPP LTE.

Key words -- Physical Layer; Long Term Evolution; 3GPP; SC-FDMA; OFDM

1. Introduction

Majority of the mobile broadband consumers will be served by LTE networks in the near future .With this technology users can readily access internet services like social networking , online gaming , mobile video blogging and other professional services. LTE has uplink speed of up to 50 megabits per second and download speed of up to 100 megabits per second. It has scalable bandwidth that enables service providers to provide different services on the basis of spectrum.

Physical Layer of LTE is efficient mean of sending data and control signals between base station and user mobile. LTE uses many advance technologies including Orthogonal Frequency Division Multiplexing (OFDM) and Multiple Input Multiple Output (MIMO).Besides these on uplink it employs Single Carrier Frequency Division Multiple Access (SC-FDMA) while on download link it uses Orthogonal Frequency Division Multiple Access (OFDMA). Majority of LTE based networks uses frequency division multiplexing (FDD).

Before OFDM, single carrier modulation technique is used in cellular systems. Inter Symbol interference, caused by multipath effects, in which symbols interfere with one another to produce the noise like effect cannot be reduced by using this technique. This is because all new technologies require very high data rates. As data rate increases symbol duration becomes shorter thus it is possible that interference occurs after skipping some symbols which rise to more severe form of ISI [1].

2. Orthogonal Frequency Division Multiplexing (OFDM)

Orthogonal Frequency Division Multiplexing technique can reduce this problem .It is bandwidth efficient technique (fig-1) which does not increase the symbol rate for increasing data rate. It splits the data into multiple streams by breaking the bandwidth into narrow subcarriers and transmits the data on these streams. For better utilization of bandwidth sub-carriers in OFDM are very closely spaced. Despite the fact that they are very closely spaced they do not interfere with one another because the frequencies of sub carriers are orthogonal to one another. It means that the peak of one sub carrier will be on the null of the consecutive sub carrier. Another reason for reduction of ISI in OFDM is cyclic prefix also called guard interval. It is copy of last portion of the symbol and appended in front of that symbol. It avoids Inter Carrier Interference (ICI), the interference of one sub carrier in OFDM data stream with other.The length of the cyclic prefix must be greater than the highest amount of delay spread by the channel as carriers cannot interfere with other carriers in this way but only with the cyclic prefix. This interference is then corrected by determining the impulse response of the channel. Some drawbacks of this technique are high peak to average power ratio (PAPR), small carrier frequency offsets and sampling clock offsets. IEEE 802.16 d uses this technique as standard [2].

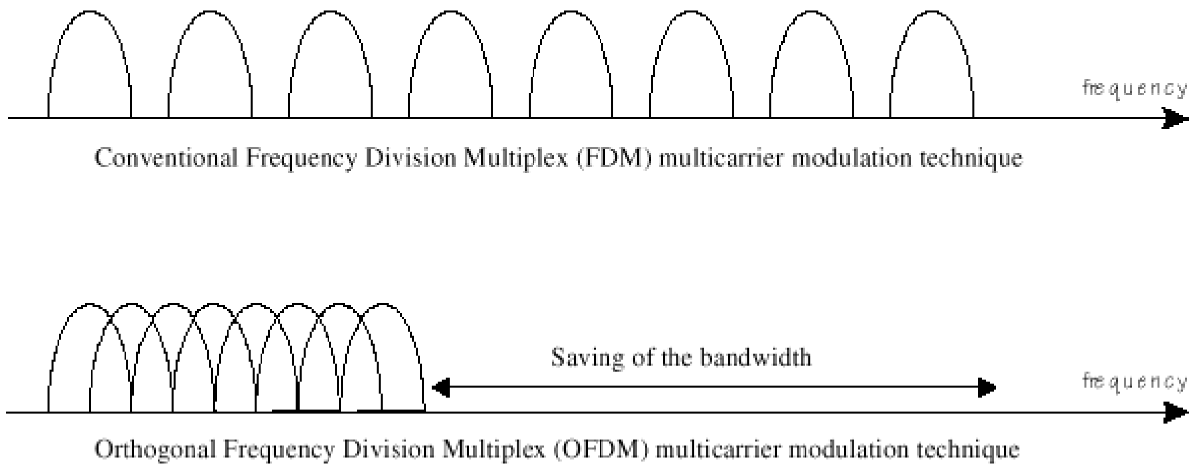

Fig.1 Conventional FDM vs. OFDM

2.1 Orthogonal Frequency Division Multiple Access (OFDMA)

Wireless cellular systems are multiuser systems today. Multiple users can take the advantage of OFDM technology by using Orthogonal Frequency Division Multiple Access (OFDMA) technique. It is declared as standard of wireless communication in IEEE 802.16e. In OFDMA subcarriers are divided into further groups. These groups sub-carriers form sub-channels for different users in downlink. This is also called multiple access. These sub-carriers can be separated both in time and frequency domains as shown in fig-2 which is valid for both time and frequency domain. Major advantages of OFDMA includes its uplink orthogonality, its ability to take advantage of frequency selectiveness of channel, MIMO friendliness and provision of superior quality service [3].

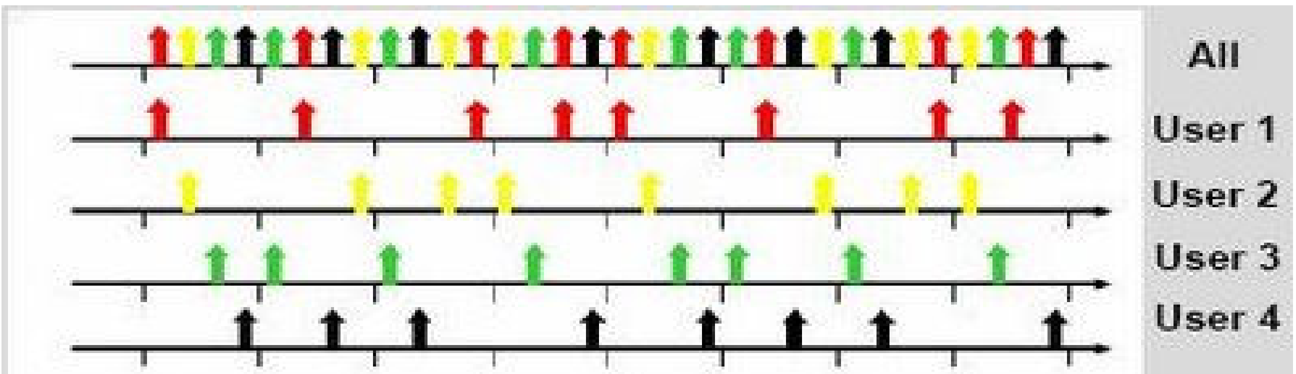

Fig.2 OFDM

2.2 Multiple Input Multiple Output (MIMO) and Maximal Ratio Combining (MRC)

Multiple antennas are used on both transmitter and receiver sides in Multiple Input and Multiple Output (MIMO) technology. This increases the data rates to very high value. It does not require increased transmit power and additional bandwidth. By using only one antenna at transmitter and receiver we can transmit only one signal at a time. Due to multipath effect scattered portions of this signal that arrive late at receiver causing effects like fading ,inter symbol interference (ISI), decrease in data speed and increase in number of error bits. By using MIMO we actually provide the receiver the multiple copies of the same signal and thus reducing the probability of distortion of these signals at the same time. It is possible to add the gain of these multiple antennas to increase the signal to noise ratio of the system. Maximal Ratio Combining (MRC) is used for this purpose. Signal is received via pair of receivers in MRC .It is used to combine signals from multiple sources. Each antenna at transmitter have different signal path to receiver and thus channel impulse responses associated with each path are distinct. Channel responses are determined by sending known reference signals from transmitter antennas sequentially. Inverse of channel response is applied to each signal at baseband processor of receiving antenna to make them coherent. For two channel MRC receiver, this results increase in SNR of about 3dB.MRC just enhances the reliability of our channel while MIMO increases the data rate.

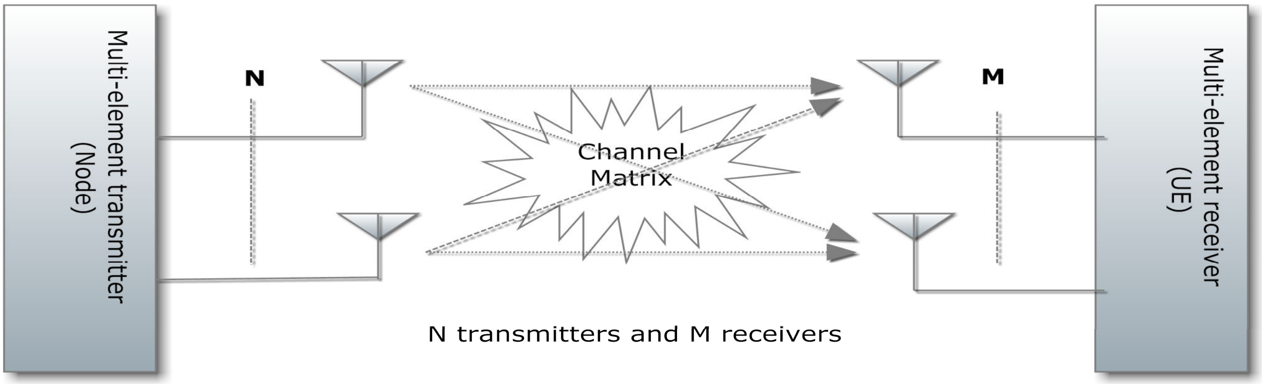

Fig.3 Multiple Input Multiple Output Transmitter and Receiver

2.3 Single Carrier Frequency Division Multiple Access (SC-FDMA)

Due to power consumption problem and high peak to average power ratio of OFDM , 3GPP uses Single Carrier Frequency Division Multiple Access (SC-FDMA)on its for Uplink (UE).Difference between the OFDM and SC-FDMA is DFT-Mapper in the SC-FDMA transmitter. Transmitter form the groups of modulation symbols after mapping data on these symbols . Thus in this technique multiple sub carriers carry same data symbol. These symbols in time domain are converted into frequency domain by DFT mapper. These frequency domain symbols are then mapped on to subset M of subcarriers. Usually M is greater than N.IFFT is then used to convert these time domain signals into frequency domain followed by cyclic prefix, parallel to serial convertor, digital to analogue convertor and RF subsystems.SC-FDMA is also called DFT precoded OFDM .It also offers spreading gain as each symbol is mapped on group of sub carrier in frequency domain. Sub carrier mapping is of two types *localized* mapping and *distributive* mapping. In *localized* mapping output from the DFT mapper are mapped on the consecutive symbols thus this mapping is limited to small portion of the system bandwidth. In *distributed* mapping data in symbol is assigned to sub carriers in the entire bandwidth [3].

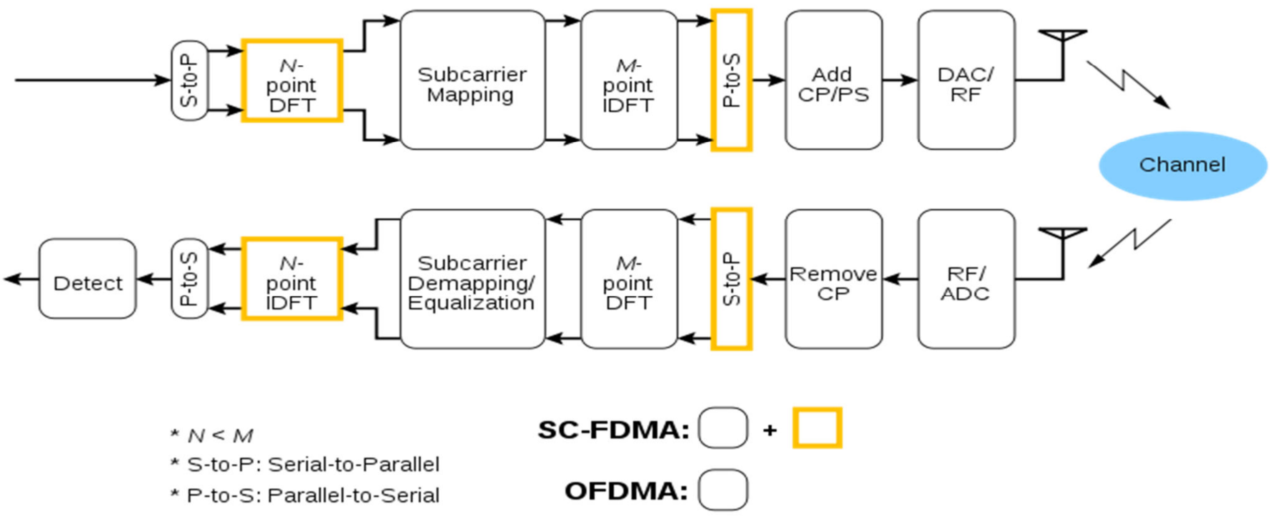

Fig.4 Transmitter and Receiver End of (SC-FDMA)

3. LTE Generic Frame Structure

Genetic Frame Structure for both the uplink and downlink is same. Physical resource Carriers (PRB) are group of sub carriers assigned to the same user for some specific amount of time. They have both frequency and time domains. Data in LTE network is transmitted in the form of frames of duration 10ms. Frame is further divided into 10 sub-frames of duration 1 ms. Each sub frame has two slots of duration 0.5ms.For normal cyclic prefix slot contain 7 OFDM symbols while for extended cyclic prefix it contains 6symbols. Space between sub carrier is 15kHz and PRB bandwidth is 180kHz.Thus PRB consists of 12 consecutive sub carriers for 0.5ms duration slot. Total number of sub carriers depends on the system bandwidth. PRBs also contain reference signals in itself to estimate channel response, time synchronization etc. In time domain they are transmitted during first and fifth OFDM symbols when short cyclic prefix is used and during first and fifth when long cyclic prefix is used while in frequency domain on every 6^{th} sub carrier. Receiver can compute the channel response of symbols having reference signals directly.

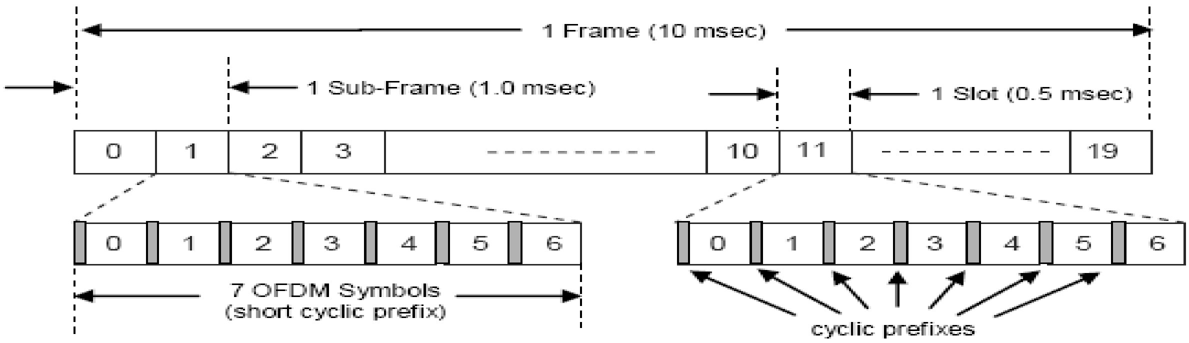

Fig.5 LTE Frame Structure

3.1 Downlink

LTE have bandwidth from 1.25 MHz to 20 MHz .As stated earlier OFDMA is used as multiplexing technique in downlink. Modulation technique used for downlink is OFDM with sub carrier spacing of 15 kHz. Modulation parameters are summarized in Table 1.

Table.1 Modulation Parameters of OFDM in Downlink

Transmission Bandwidth (MHz)	1.25	2.5	5	10	15	20
Sub Carrier Spacing(kHz)	15					
Sub Frame Duration (ms)	0.5					
Sampling Frequency (MHz)	1.92MHz (0.5x3.84 MHz)	3.84MHz (1x3.84 MHz)	7.68MHz (2x3.84 MHz)	15.36MHz (4x3.84 MHz)	23.04MHz (6x3.84 MHz)	30.72MHz (8x3.84 MHz)
FFT size	128	256	512	1024	1536	2048
Short Cyclic prefix length()	(4.69/9) x 6, (5.21/10) x1	(4.69/18)x6 (5.21/20)x 1	(4.69/36)x6 (5.21/40)x 1	(4.69/72)x6 (5.21/80)x 1	(4.69/108)x6 (5.21/120)x1	(4.69/144)x6 (5.21/160)x 1
Long Cyclic prefix length()	16.67/32	16.67/32	16.67/32	16.67/32	16.67/32	16.67/32
OFDM symbol per slot (long short CP)	6/7					

Use of short or long CP depends on delay spread of channel. Cyclic prefix of first OFDM symbol is longer than that of other symbols if short CP is used to make time duration of time slot 0.5ms.

Table.2 Cyclic Prefix Duration

Configuration		Cyclic Prefix Length	
Normal CP	Δf = 15kHz	Ts 160 for I = 0 144 for I = 1,2 ….5	μsec 5.21 for I = 0 4.69 for I = 1, 2…5
Extended CP	Δf = 15kHz	512 1024	16.67 33.33

Ts is defined as 1 / (15000 x 2048) seconds, which corresponds to the 30.72 MHz sample clock for the 2048 point FFT used with the 20 MHz system bandwidth. OFDMA is used as a multiplexing technique in downlink .Each slot contains 12 adjacent sub-carriers to form a PRB which smallest controllable unit from the base station.

3.2 Physical Channels

All information from the higher layer in LTE are conveyed through physical channels. Physical channels are of three types

1. Physical Downlink Shared Channel (PDSCH)
2. Physical Downlink Control Channel (PDCCH)
3. Common Control Physical Channel (CCPCH)

Physical channels have algorithms for modulation, CDD precoding, bit scrambling, resource element assignment and Layer mapping

3.2.1 Physical Downlink Shared Channel

Allocation to this channel to user in on dynamic basis .It supports data and multimedia transportation. , thus supports very high data rates .For forward error correction convolutional turbo encoder is employed. Multi antenna technique is used for mapping of data on the spatial layers and then mapping on modulation symbol is done through QPSK, 16-QAM and 64-QAM.

3.2.2 Physical Downlink Control Channel

Specific control information is conveyed to user by PDCCH in downlink control information message (DCI). QPSK technique is used for modulation in PDCCH. We can also transmit multiple PDCCH in same sub frame through Control Channel Elements (CCE). CCE consists of four resource elements of 9 sets known as resource element group (REG) on each of which 4 symbols of QPSK re mapped. PDCCH is mapped on three OFDM symbols in sub frame’s first slot.

3.2.3 Common Control Physical Channel

Cell wide control information are carried through this channel. CCPCH is transmitted very close to the centre frequency.72 active sub carriers are used to transmit it which are centered on DC sub carrier. Resource element (k, I) are then used for mapping this control information where k are the OFDM symbols in slot and I are sub-carriers. Mapping is based on increasing order of first k and then I.

3.3 Physical Signals

Physical signals are used for assigning resource elements. They have two types

3.3.1 Reference Signals

Channel impulse response is determined by reference signal .Product of pseudo random numerical and orthogonal sequence generates reference signals. Possible numbers of unique reference signals are 510.Every cell has unique reference signal. For accuracy of CIR from each transmitting antenna to user when one transmitting antenna transmits reference signal other transmitting antennas become idle as shown in Fig.6.

3.3.2 Synchronization Signals

Network timing information can be determined from synchronization signals. Product of pseudo random numerical and orthogonal sequence generate reference signals. Depending on their usage by user during search procedure they are classified as primary and secondary synchronization signals. They are transmitted on 0^{th} and 10^{th} slot of the frame using 72 sub carriers that are centered on DC sub carrier

3.4 Transport Channels

Higher layers of LTE used these channels as service access point (SAP). Types are *Broadcast Channel* which has to be broadcasted over entire coverage area and have fixed format. *Downlink Shared Channel* supports hybrid ARQ, dynamic resource allocation, use along beam forming. Link can be changed by varying transmit power, coding and modulation scheme. Does not need power continuously for power saving purpose. *Paging Channel (PCH)* can be mapped on dynamically allocated physical resources, covers entire cell area and provide support for user end discontinuous receive. *Multicast Channel (MCH)*

Broadcasted for Entire cell coverage, semi static resource allocation and MB-SFN support.

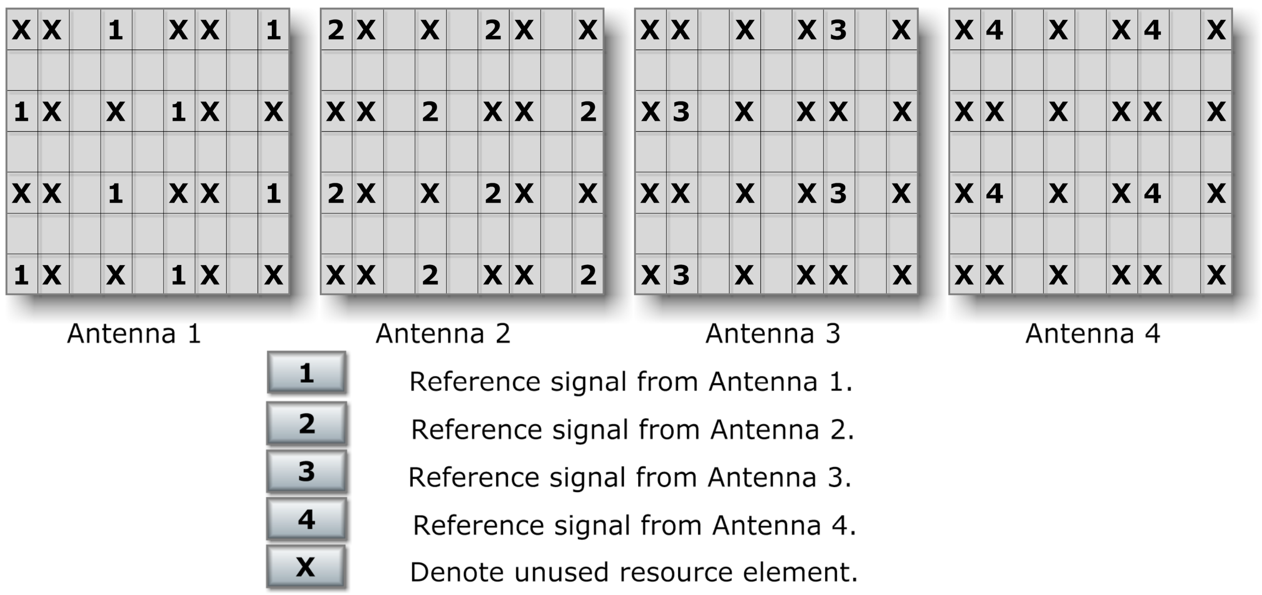

Fig.6 Resource Element Mapping of Reference Signals

3.4.1 Mapping of Downlink Physical Channels to Transport Channels

Mapping is done as shown in Fig.7. Broadcast channel, Paging Channel, Downlink Shared Channel and Multicast Channel are supported transport channels. Transport Channels also provide configuration method of PHY by higher layers, peer to peer signaling of higher layers, structure indicators to higher layers and method for passing data to/from higher layers.

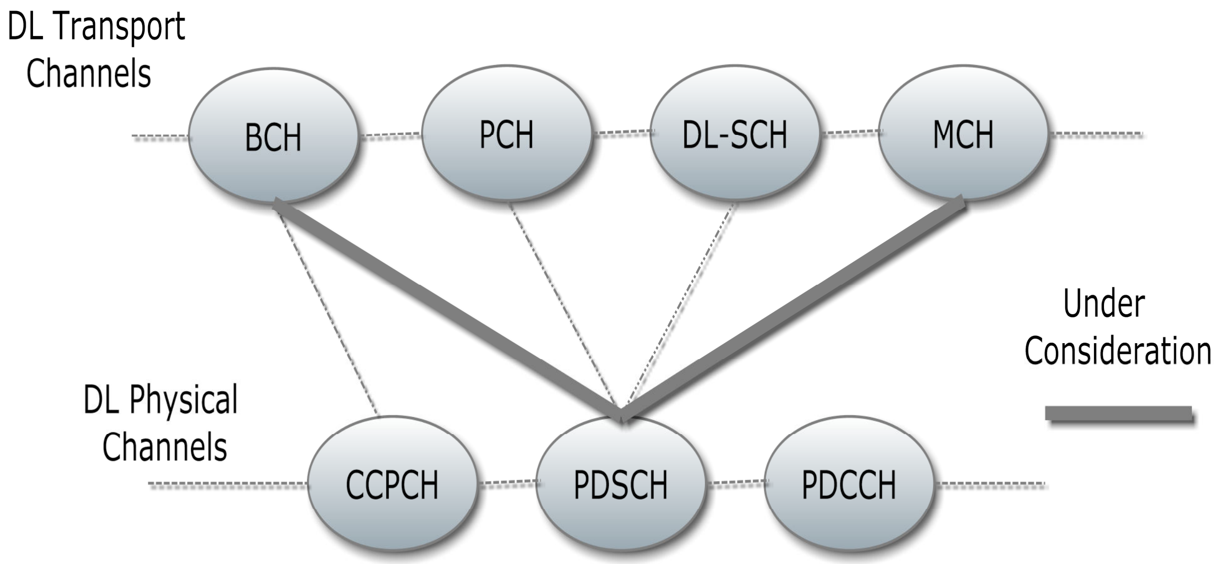

Fig.7 Mapping of DL Transport Channels to Physical Channels

3.4.2 Downlink Channel Coding

A physical channel of downlink employs many coding schemes. QPSK, and convolutional coding has been employed in CCPCH. PDSCH uses QPSK, 16QAM and 64QAM depending on the conditions of channel. For PDSCH 1/3 rate of turbo coding has been selected.

4. Uplink

LTE uplink uses SC-FDMA for data transmission instead of OFDM due to its low peak average power ratio (PAPR) value.

4.1 Modulation Parameter

Sub-carrier spacing , generic frame structure and download modulation parameters in LTE Uplink are same as in downlink however there is difference is between sub-carrier mapping. The modulated symbols are fed into DFT block sequentially. Result is discrete frequency domain representation of these symbols which then mapped on to the sub set of sub-carriers. IFFT is applied to convert them back into time domain and cyclic prefix is appended before transmitting them.

4.2 Uplink Multiplexing

Downlink CCPCH is responsible for assigning PRBs to the users in uplink. Each slot contains 12 sub carriers.

4.3 Uplink Physical Channels

Physical Uplink Shared Channel (PUSCH) have sub carriers that are in multiple of 12 and based on sub frame. Sub frames may be skipped .This channel supports QPSK, 16QAM and 64QAM modulation schemes. *Physical Uplink Control Channel (PUCCH)* PUCCH and PUSCH can never be transmitted together. This channel carry control information besides user data like acknowledgment, negative acknowledgement etc. Control data and information data are multiplexed together before DFT block.
Physical Random Access Channel carries random access preamble which user send to base station in non synchronizing mode to synchronize with the base station. In frequency domain it carries 72 subcarriers [4].

4.4 Uplink Physical Signals

Uplink Reference Signal has two variants uplink demodulation signal for coherent demodulation while sounding reference signals helps base station with channel sounding. Also it helps in time estimation, power control, antenna selection and frequency selective uplink scheduling [5]. Both are based on Zadhoff-Chu sequence. *Random Access preamble* is sent by UE to MAC layer in downlink and if received get random access response from PDCCH in uplink from the MAC layer of LTE. Its format is shown in Fig.8.

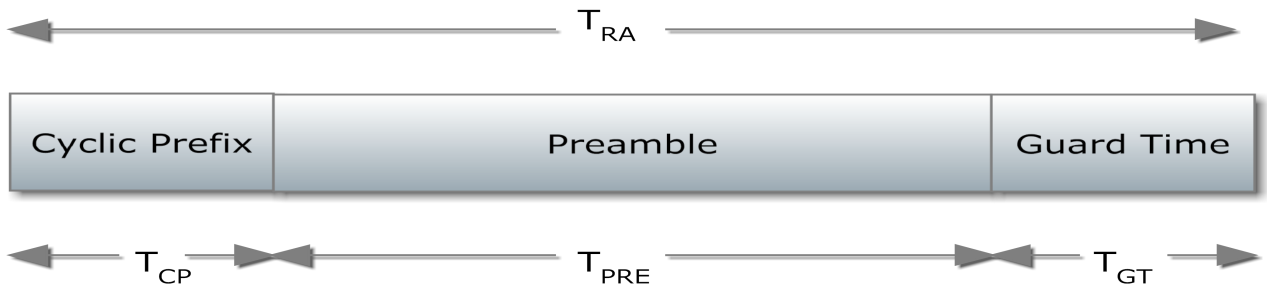

Fig.8 Random Access Permeable Format

Timings are T_{RA} = $30720T_S$, T_{PRE} = $24576T_S$, T_{GT} = $3152T_S$ where T_S is period of 30.72MHz clock. 64 preamble sequences in the cell are possible in FDD. Frequency on which it is transmitted in the UE is selected by higher layers of UE from random access channel. Information regarding to Preamble format, power ramp step size, initial transmission power, maximum number of retires and available random access channel are also provided by higher Layer to PHY layer.

4.5 Uplink Transport Channel

Uplink Shared Channel Provide support for beam-forming, HARQ and dynamic link adaption. *Random Access Channel* support limited control information along with collision risk.

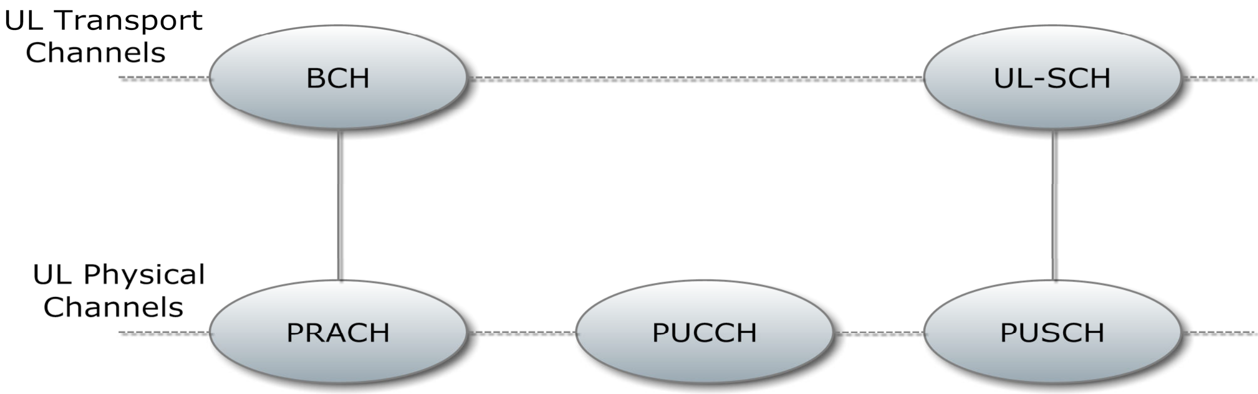

Fig.9 Mapping of Uplink Physical Channels to Transport Channels

4.6 Coding

Turbo encoding is used in UL-SCH with rate 1/3 as compared to DL-SCH.

4.7 MB-SFN

Multimedia broad cast multi cast services makes broad cast and multicast services more efficient within the cell or within the core network. In core network or multi-cell transmissions MBMS is synchronized to form Multicast/Broadcast – Single Frequency Network (MB-SFN). It sends data on synchronized single frequency network using OFDM radio interface. Very little inter symbol interference is caused when user is at the boundary of the two or more cells because the delay between two signals of the cell is comparatively less than when user is very close to one cell[5].

5. Conclusion

Long term evolution 4G is a major advancement in the cellular technology. It is designed to meet high speed data and multimedia unicast and broadcast services. It is superior to 3G technology as it employs advanced technologies including OFDM and MIMO that have very high data rates as compared to traditional techniques. On downlink OFDMA and on uplink SC-FDMA is employed. Other features which make it superior to 3G are scalable bandwidth, Peak data rate, antenna configurations supported and spectrum efficiency.

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