LTE BASEBAND ALGORITHMS FOR UPLINK

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Approval Sheet

This thesis entitled " LTE Baseband Algorithms for Uplink" by Paramatmuni Pavan Karthik is approved for the degree of "**Master of Technology**" from IIT Hyderabad.

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Abstract

LTE is a next generation mobile system from the 3GPP with a focus on wireless broadband.The aim of LTE is to achieve high data rates in both uplink & downlink, and to achieve high spectral efficiencies.The main focus of the work is to develop baseband algorithms in the uplink in order to achieve uplinksynchronization between the user and the base station and also for the detection of the control data that is transmitted.

For the base station to obtain the knowledge of the presence of the user and also about its position, the user has to transmit synchronization signals to the base station, which are transmitted on the Physical Random Access CHannel (PRACH) in LTE. These signals are used to obtain the uplink timing correction and hence synchronize with the base station.

It is very important for the base station to detect the control data that has been transmitted by the user on Physical Uplink Control CHannel (PUCCH). The control data may consist of the response of the UE to the data packets that were transmitted by the base station, request for resource allocation etc.So efficient algorithms are necessary for the accurate detection of the control data at the base station.

The current work presents algorithms that are essential for obtaining uplink synchronization and also for efficient detection of the control channel data.

Contents

Chapter 1

Introduction to LTE (Long Term Evolution)

LTE stands for Long Term Evolution and it was started by the telecommunications body Third Generation Partnership Project (3GPP). The main goal of LTE is to provide a high data rate, low latency and packet optimized radio access technology supporting flexible bandwidth deployments. Same time its network architecture has been designed with the goal to support packet-switched traffic with seamless mobility and great quality of service. It provides an uplink speed of up to 50 megabits per second (Mbps) and a downlink speed of up to 100 Mbps. LTE will bring many technical benefits to cellular networks. Bandwidth will be scalable from 1.25 MHz to 20MHz. This will suit the needs of different network operators that have different bandwidth allocations, and also allow operators to provide different services based on spectrum.

The LTE PHY(Physical Layer) is a highly efficient means of conveying both data and control information between an enhanced base station (eNodeB) and mobile user equipment (UE). The LTE PHYemploys some advanced technologies that are new to cellular applications. These include Orthogonal Frequency Division Multiplexing (OFDM) and Multiple Input Multiple Output (MIMO) data transmission.

1.1 Advantages of LTE:

1. High throughput: High data rates can be achieved in both downlink as well as uplink. This causes high throughput.
2. Low latency: Time required to connect to the network is in range of a few hundred milliseconds and power saving states can now be entered and exited very quickly.
3. FDD and TDD: Frequency Division Duplex (FDD) and Time Division Duplex (FDD), both schemes can be used on same platform.
4. High spectral efficiency: The spectral efficiency associated with the high data rates is also high.
5. Simple architecture: Because of Simple architecture low operating expenditure (OPEX).
6. Plug and play: The user does not have to manually install drivers for the device. Instead system automatically recognizes the device, loads new drivers for the hardware if needed, and begins to work with the newly connected device.

1.2 Basic LTE parameters:

1.2.1 Time domain:

In LTE, the resources in the time domain are allocated in terms of subframes.

Frame:

A frame in LTE corresponds to time duration of 10ms.

1 Frame=10ms

Sub-Frame:

A frame is further divided into 10 sub-frames. So, the duration of 1 sub-frame is 1ms.

1 Sub-Frame=1ms

Slot:

Slot in LTE is defined as time resource of 0.5ms.Thus a sub-frame consists of 2 slots.

1Slot=0.5ms

Slot is composed of 7(or 6) OFDM symbols in case of normal CP (extendCP). Frame structure is represented in fig 1.1

Frame structure:

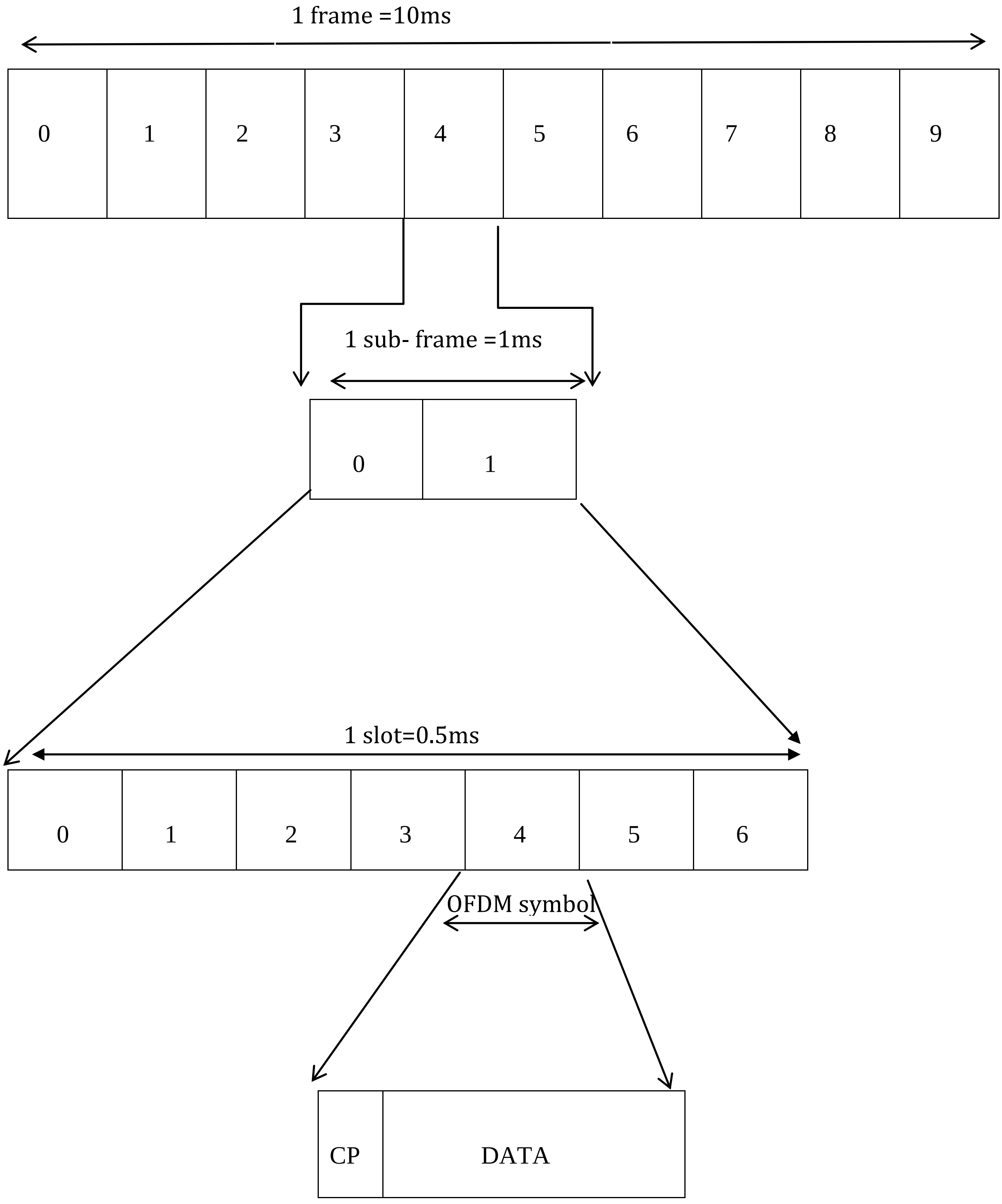


Figure 1.1 : Frame structure

1.2.2 Frequency domain:

In frequency domain , the frequency resources are allocated in terms of subcarriers. The sub carrier spacing defined in LTE 15KHz. Minimum number of 12 sub-carriers are allocated to each user for their transmission and it is called as resource block.

1 Resource Block=12 Sub-Carriers

=12 * 15 KHz

= 180 KHz.

LTE supports flexible bandwidths,it is shown in table 1.1.

Table 1.1: Bandwidths supported by LTE

System Bandwidth(MHz)	No of Resource Blocks(RBs)
1.4	6
3	15
5	25
10	50
15	75
20	100

Resource Grid:

LTE allocated resources in both time and frequency dimensions as shown in fig 1.2

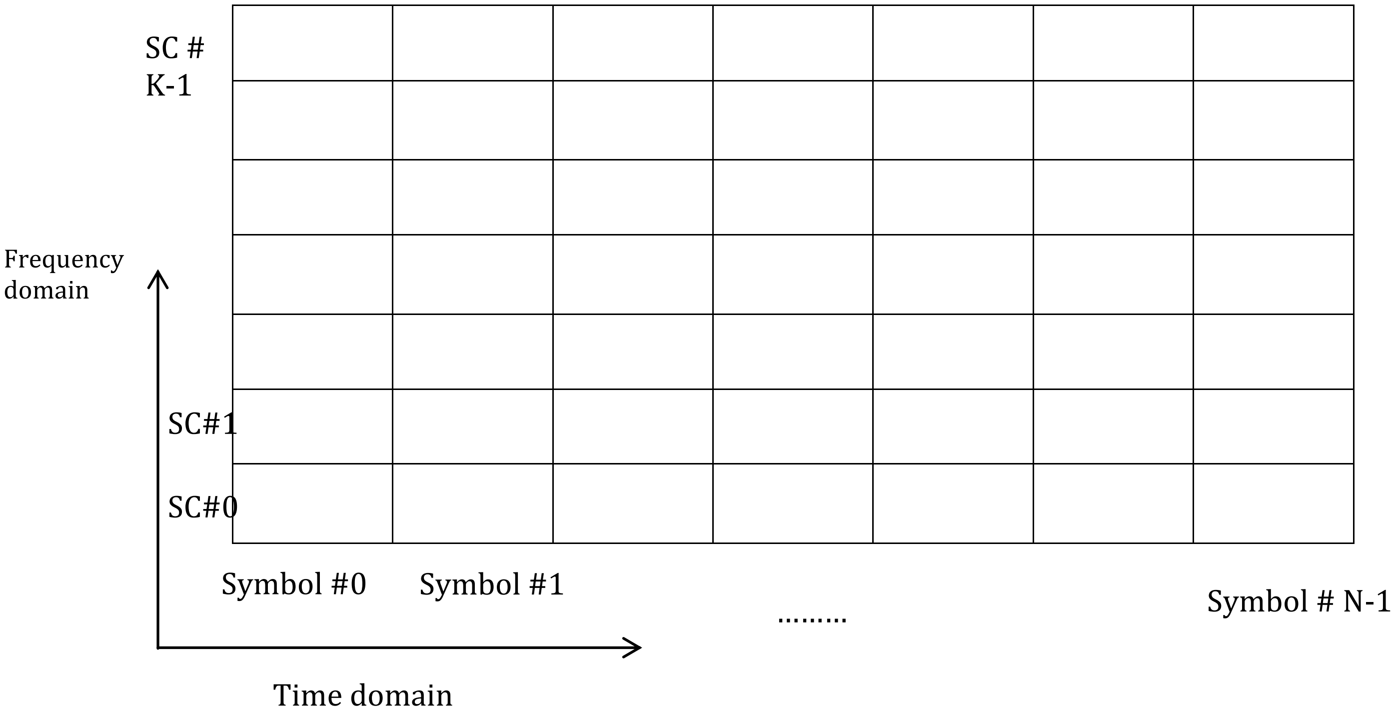


Figure 1.2: Resource grid

1.3 Transmission Time Interval:

In LTE, Transmission Time Interval denotes the minimum length of individually decodable transmission link. It is defined as 1 sub-frame i.e., 1ms.
Minimum resource that can be allocated in LTE is:

- Time: 1 sub-frame (1 ms).
- Frequency: 12 subcarriers (180 KHz).

1.4 Multiple Access schemes employed in LTE:

In order to achieve the high data rates that are achieved in LTE the following multiple access schemes are employed.

- OFDMA(Orthogonal Frequency Division Multiple Access)-This is employed in downlink

- SC-FDMA (Single Carrier Frequency Division Multiple Access)- This is employed in the uplink.

1.5 Physical Channels:

LTE defines various physical channels in uplink and downlinks for the transmission of various signals.

1.5.1 Physical channels in downlink:

1. Physical Downlink Shared Channel(PDSCH)
2. Physical Broadcast Channel (PBCH).
3. Physical Downlink Control Channel (PDCCH).
4. Physical Multicast Channel (PMCH).
5. Physical Control Format Indicator Channel (PCFICH).
6. Physical Hybrid ARQ indicator Channel (PHICH).

PDSCH:

This channel carries the traffic data from the eNodeB to the UEs. This channel is shared between different users in both time and frequency domain. PDSCH supports QPSK, 16-QAM, 64-QAM modulation schemes.

PBCH:

This channel is used for the transmission of the data that is specific to a cell such as its ID, system bandwidth etc. It supports only QPSK modulation.

PDCCH:

This channel is used for the transmission of the control information and also the information related to resource allocation. It carries information in 1 or more control channel elements where each control channel element corresponds to 9 Resource Element Groups (REGs) and in turn each REG corresponds to 4 Resource Elements (REs). It supports only QPSK modulation.

PMCH:

This channel is similar to PDSCH except that this carries information to multiple users for point-to-multipoint broadcast services. It uses QPSK, 16-QAM, 64-QAM.

PCFICH:

This is a physical channel that carries the number of OFDM symbols that are used for the transmission of PDCCH in a sub-frame. PCFICH is located at symbol 0 of every sub-frame while the frequency resources are determined by the CELL-ID.

PHICH:

This carries the acknowledgement in response to the data that is received by eNodeB in the uplink that is transmitted by the UE.

1.5.2 Physical Channels in uplink:

1. Physical Random Access Channel (PRACH).
2. Physical Uplink Control Channel (PUCCH).
3. Physical Uplink Shared Channel (PUSCH).

PRACH:

This channel initiates the communication of the user with the eNodeB. This channel allows the eNodeB to calculate the time delay to the eNodeB and hence to adjust the timing between both the UE and eNodeB, thus playing a major role in the establishment of uplink-timing synchronization.

PUCCH:

This channel is used for the transmission of the uplink control information from the user to the eNodeB which includes the scheduling requests, channel state information and the acknowledgement to the packets that are received in the downlink. The modulation schemes that are supported by PUCCH are BPSK, QPSK.

PUSCH:

This channel is used for the transmission of the uplink data from the user. Upon request from the eNodeB, this can also be used for the transmission of the uplink control information (UCI). PUSCH supports QPSK, 16-QAM, 64-QAM.

Chapter 2

OFDM and SC-FDMA

2.1 OFDM

OFDM is simply defined as a form of multi-carrier modulation where the carrier spacing is carefully selected so that each sub carrier is orthogonal to the other sub carriers. Two signals are orthogonal if their dot product is zero. That is, if you take two signals multiply them together and if their integral over an interval is zero, then two signals are orthogonal in that interval. Orthogonality can be achieved by carefully selecting carrier spacing, such as letting the carrier spacing be equal to the reciprocal of the useful symbol period. As the sub carriers are orthogonal, the spectrum of each carrier has a null at the center frequency of each of the other carriers in the system.

Two periodic signals are orthogonal when the integral of their product over one period is equal to zero. For the case of continuous time:

$$\int_{0}^{T} \cos(2\Pi n f o t) \cos(2\Pi m f o t)\, dt = 0,$$

For the case of discrete time:

$$\sum_{k=0}^{N-1} \cos\left(\frac{2\pi k n}{N}\right) \cos\left(\frac{2\pi k m}{N}\right) dt = 0,$$

Where m≠n in both cases.

OFDM transmits a large number of narrowband sub channels. The frequency range between carriers is carefully chosen in order to make them orthogonal one another. In fact, the carriers are separated by an interval of 1/T, where T represents the duration of an OFDM symbol. The frequency spectrum of an OFDM transmission is illustrated in figure 2.1.

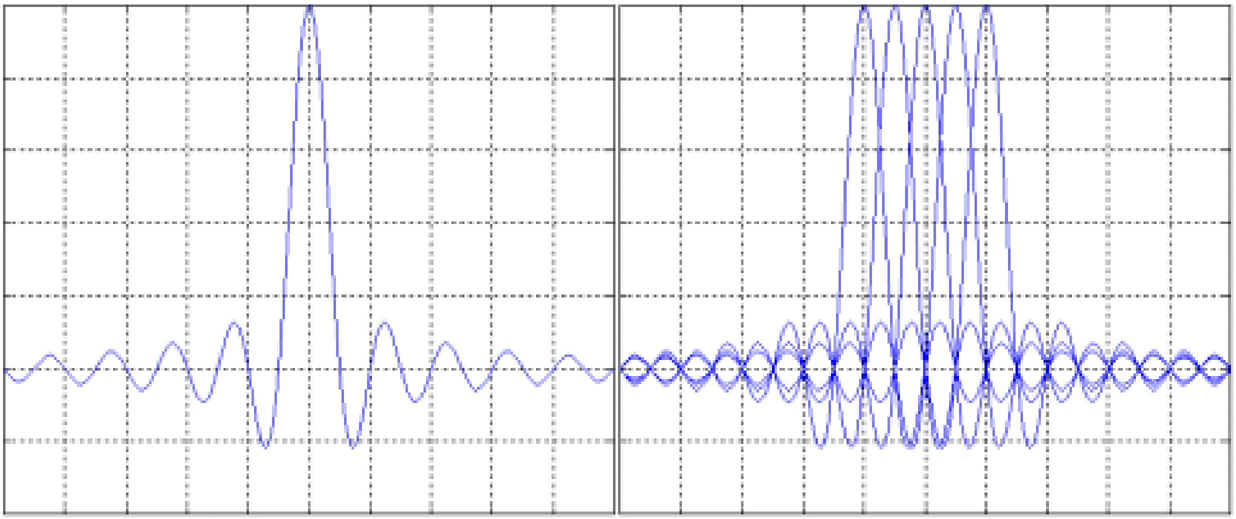


Fig 2.1 Spectra of a sub-channel and OFDM signal

Each sub – carrier in an OFDM system is a sinusoid with a frequency that is an integer multiple of a fundamental frequency. Each sub – carrier is like a Fourier series component of the composite signal, an OFDM symbol.

The sub – carriers waveform can be expressed as

$$\mathrm{s(t)} = \cos(2\pi f c t + \theta k)$$

$$= a_n \cos(2\pi n f_o t) + b_n \sin(2\pi n f_o t)$$

$$= \sqrt{a_n^2 + b^2 n}\cos(2\pi n f_o t + \varphi),$$

Where $\varphi = \tan^{-1}(\frac{bn}{an})$

The sum of sub carrier is the baseband OFDM signal

$$s(t) = \sum_{n=0}^{N-1} \{a_{n\cos(2\pi n f_o t) - b_n \sin(2\pi n f_o t)}\}$$

Each sinc of the frequency spectrum in the Fig 2.1 corresponds to a sinusoidal carrier modulated by a rectangular waveform representing the information symbol.

One could easily notice that the frequency spectrum of one carrier exhibits zero-crossing at central frequencies corresponding to all other carriers. At these frequencies, the intercarrier interference is eliminated, although the individual spectra of subcarriers overlap. It is well known, orthogonal signals can be separated at the receiver by correlation techniques. The receiver acts as a bank of demodulators, translating each carrier down to baseband, the resulting signal then being integrated over a symbol period to recover the data. If the other carriers all beat down to frequencies which, in the time domain means an integer number of cycles per symbol period (T), then the integration process results in a zero contribution from all these carriers.

Principle of OFDM:

In a conventional serial data system, the symbols are transmitted sequentially, one by one, with the frequency spectrum of each data symbol allowed to occupy the entire available bandwidth. A high rate data transmission supposes very short symbol duration, conducing at a large spectrum of the modulation symbol. There are good chances that the frequency selective channel response affects in a very distinctive manner the different spectral components of the data symbol, hence introducing the ISI. The same phenomenon, regarded in the time domain consists in smearing and spreading of information symbols such, the energy from one symbol interfering with the energy of the next ones, in such a way that the received signal has a high probability of being incorrectly interpreted. Intuitively, one can assume that the frequency selectivity of the channel can be mitigated if, instead of transmitting a single high rate data stream, we transmit the data. Simultaneously, on several narrow-band subchannels (with a different carrier corresponding to each subchannel), on which the frequency response of the channel looks “flat”. Hence, for a given overall data rate, increasing the number of carriers reduces the data rate that each individual carrier must convey, therefore lengthening the symbol duration on each subcarrier. Slow data rate (and long symbol duration) on each subchannel merely means that the effects of ISI are severely reduced. This is in fact the basic idea that lies behind OFDM. Transmitting the data among a large number of closely spaced subcarriers accounts for the “frequency division multiplexing” part of the name. Unlike the classical frequency division multiplexing technique, OFDM will provide much higher bandwidth efficiency. This is due to the fact that in OFDM the spectra of individual subcarriers are allowed to overlap. In fact, the carriers are carefully chosen to be orthogonal one another. As it is well known, the orthogonal signals do not interfere, and they can be separated at the receiver by correlation techniques.

The input data sequence is baseband modulated, using a digital modulation scheme. Various modulation schemes could be employed such as BPSK, QPSK (also with their differential form) and QAM with several different signal constellations. There are also forms of OFDM where a distinct modulation on each subchannel is performed. The modulation is performed on each parallel substream that is on the symbols belonging to adjacent DFT frames. The data symbols are parallelized in N different substreams. Each substream will modulate a separate carrier through the IFFT modulation block.

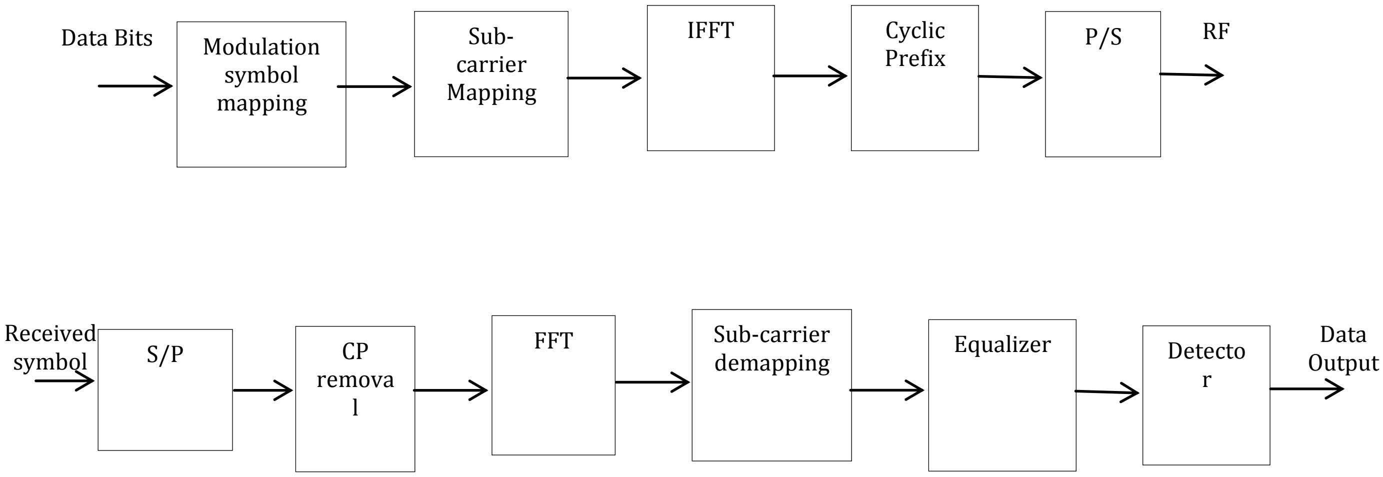


Figure 2.2 : Modulation and Demodulation in OFDM

2.2 Cyclic Prefix :

The Cyclic Prefix or Guard Interval is a periodic extension of the last part of an OFDM symbol that is added to the front of the symbol in the transmitter, and is removed at the receiver before demodulation.

The cyclic prefix has to two important benefits –

- The cyclic prefix acts as a guard interval. It eliminates the inter – symbol interference from the previous symbol.

- It acts as a repetition of the end of the symbol thus allowing the linear convolution of a frequency – selective multipath channel to be modeled as circular convolution which in turn maybe transformed to the frequency domain using a discrete Fourier transform. This approach allows for simple frequency – domain processing such as channel estimation and equalization.

Disadvantages of OFDM:

1. High peak to average power ratio.
2. Susceptible to synchronization errors such as frequency offset.

In order to overcome the high PAPR problem, LTE has adopted SC-FDMA as the multiple-access technique using which the power amplifier at mobile terminals employing SC-FDMA can be simpler and more power-efficient than they would be with OFDMA transmission.

2.3 SC-FDMA:

2.3.1 Introduction:

The multi-carrier scheme that is employed in the uplink is SC-FDMA. The reason for employing this scheme is that it provides the following advantages:

1. Orthogonal uplink transmission by different User Equipment (UEs), to minimize intra-cell interference and maximize capacity;
2. Flexibility to support a wide range of data rates, and to enable the data rate to be adapted to the Signal-to-Interference-plus-Noise Ratio (SINR);
3. Sufficiently low Peak-to-Average Power Ratio (PAPR) of the transmitted waveform, to avoid excessive cost, size and power consumption of the UE Power Amplifier.
4. Ability to exploit the frequency diversity afforded by the wideband channel (up to 20 MHz), even when transmitting at low data rates.
5. Support for frequency-selective scheduling;
6. Support for advanced multiple-antenna techniques, to exploit spatial diversity and enhance uplink capacity.

SC-FDMA combines the desirable characteristics of OFDM with the low PAPR of single-carrier transmission schemes. Like OFDM, SC-FDMA divides the transmission bandwidth into multiple parallel subcarriers, with the orthogonality between the subcarriers being maintained in frequency selective channels by the use of a Cyclic Prefix (CP) or guard period. The use of a CP prevents Inter-Symbol Interference (ISI) between SC-FDMA information blocks. It transforms the linear convolution of the multipath channel into a circular convolution, enabling the receiver to equalize the channel simply by scaling each subcarrier by a complex gain factor. Unlike OFDM, where the data symbols directly modulate each subcarrier independently (such that the amplitude of each subcarrier at a given time instant is set by the constellation points of the digital modulation scheme), in SC-FDMA the signal modulated onto a given subcarrier is a linear combination of all the data symbols transmitted at the same time instant. Thus in each symbol period, all the transmitted subcarriers of an SC-FDMA signal carry a component of each modulated data symbol. This gives SC-FDMA its crucial single-carrier property, which results in the CM/PAPR being significantly lower than pure multicarrier transmission schemes such as OFDM.

2.3.2 Structure of Transmitter:

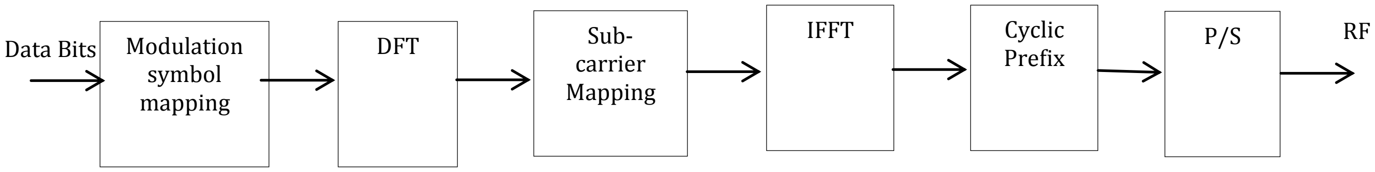


Figure 2.3 : SC-FDMA transmitter

SC-FDMA is a new multiple access technique that utilizes single carrier modulation, DFT spread orthogonal frequency multiplexing, and frequency domain equalization. It has a similar structure and performance as OFDM. SC-FDMA can be considered as an OFDM system with a DFT mapper.

Transmitter includes a baseband modulator,DFT mapper, subcarrier mapping, inverse Fourier transform, cyclic prefix addition,parallel to serial converter. Unlike other modulation techniques that operate symbol by symbol, SC-FDM transmits a block of data symbols simultaneously over one SC-FDM symbol. A SC-FDM symbol is the time used to transmit all of subcarriers that are modulated by the block of input data symbols. In LTE the baseband modulator transforms the input binary bits into a set of multi-level complex numbers that corresponds to different modulations formats such as, QPSK, 16- or 64-QAM.

The type of modulation format used often depends on the signal-to-noise level of the received signal and the receiver ability to decode them correctly. These modulated symbols are then mapped to subcarriers. An inverse-FFT (IFFT) is used to transform the modulated subcarriers in frequency domain to time domain samples.

In general, the same modulation format is used in all the subcarriers to keep the control information overhead small. However, it is possible to have different modulation formats over multiple subcarriers, and it is in fact advantageous in harsh and time varying channel conditions. In a broadband system, the channel is frequency selective over its large system bandwidth, meaning the signal fading on each subcarrier is independent. The interference level on each subcarrier can also be different and vary uniquely with time. It results in a different signal-to-impairment level on each of the subcarriers. Hence, having an appropriate modulation format on these subcarriers would help to maximize the overall system throughput. This system inherits an adaptation of modulation formats to each of the subcarriers depending on channel conditions, and this is called Channel-dependent scheduling.

A cyclic prefix block copies a portion of the samples at the end of the time domain samples block (at the IFFT output) to the beginning. Since the DFT/FFT outputs are periodic in theory, copying the samples to the beginning will make the signal continuous. The length of the cyclic prefix depends on the channel delay spread, and is preferably longer than the length of the channel response. At the receiver, the prefix part of the symbol is thrown away as it may contain ISI from its previous symbol. Hence, it removes the effect of ISI caused by the multipath signal propagation. However, the prefix is the overhead in the system, as it does not carry any useful information.

Subcarrier Mapping:

DFT output of the data symbols is mapped to a subset of subcarriers, a process called subcarrier mapping. The subcarrier mapping assigns DFT output complex values as the amplitudes of some of the selected subcarriers. Subcarrier mapping can be classified into two types: localized mapping and distributed mapping. In localized mapping, the DFT outputs are mapped to a subset of consecutive sub-carriers thereby confining them to only a fraction of the system bandwidth. In distributed mapping, the DFT outputs of the input data are assigned to subcarriers over the entire bandwidth non-continuously, resulting in zero amplitude for the remaining subcarriers. A special case of distributed SC-FDMA is called interleaved SC-FDMA, where the occupied subcarriers are equally spaced over the entire bandwidth.

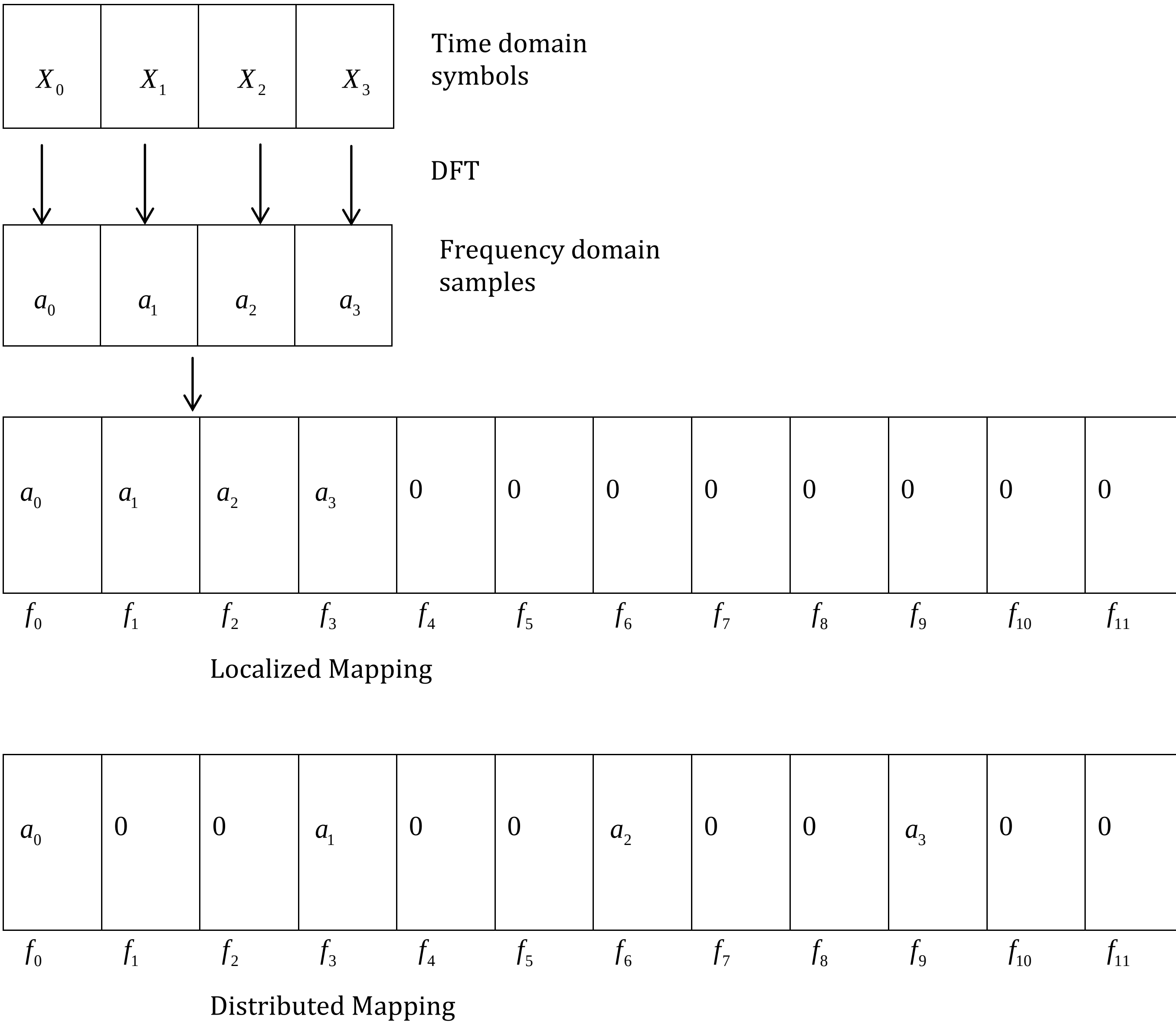


Figure 2.4 : Sub-Carrier mapping

2.3.3 Receiver Structure in SC-FDMA:

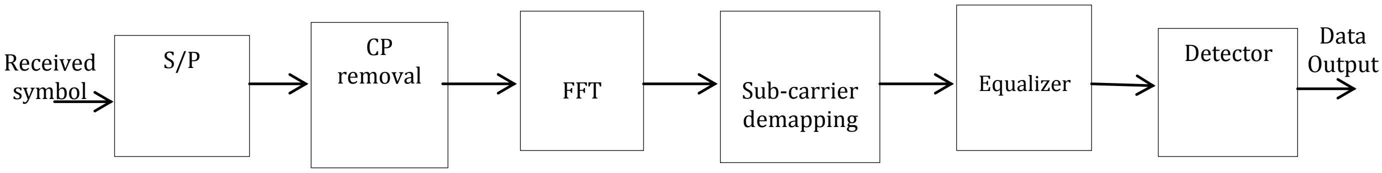


Figure 2.5 : Receiver structure

The SC-FDMA receiver consists of Serial to parallel converter, CP removal block,FFT block,sub-carrier demapper, equalizer to mitigate the effects of the channel, detector.

2.3.4 PAPR of SC-FDMA:

SC-FDMA offers similar performance and complexity as OFDM. However, the main advantage of SC-FDMA is the low PAPR (peak-average-power ratio) of the transmit signal. PAPR is defined as the ratio of the peak power to average power of the transmit signal. As PAPR is a major concern at the user terminals, low PAPR makes the SC-FDMA the preferred technology for the uplink transmission. PAPR relates to the power amplifier efficiency at the transmitter, and the maximum power efficiency is achieved when the amplifier operates at the saturation point. Lower PAPR allows operation of the power amplifier close to saturation resulting in higher efficiency. With higher PAPR signal, the power amplifier operating point has to be backed off to lower the signal distortion, and thereby lowering amplifier efficiency. As SC-FDMA modulated signal can be viewed as a single carrier signal, a pulse shaping filter can be applied to transmit signal to further improve PAPR.

Chapter-3

PRACH(Physical Random Access Channel)

3.1 Introduction :

Prach is the uplink channel that is used for initial communication between the UE and the eNodeB. The fundamental role of RACH is to act as an interface between a non-synchronized UE and eNodeB. In short, its primary function is to establish initial network access in LTE. Apart from initial network access it is also used for timing adjustment in the transmissions of UE in order to obtain uplink timing synchronization.

Scenarios in which RACH is used:

1. UE and eNodeB are in connected state but:
    - UE is not uplink synchronized and it needs to send data (using PUSCH) or control information (using PUCCH).
    - UE is not uplink synchronized and needs to send acknowledgement to the data received in the downlink
    - For adjustment of timing advancement when the UE is moving within a cell.
    - When it is handing over from one cell to another.
2. UE is not in connected state and needs to get initial access to the system and also to track area updates.
3. Radio link failure has occurred and UE tries to get recover from the failure.

3.2 Random Access Procedure:

The signal that is transmitted by the UE on the PRACH is known as the random access preamble (Each cell can support a maximum of 64 random access preamble signatures in LTE). The transmission of the preamble and its detection at the eNodeB and subsequent responses are together constitute the Random access procedure.

In LTE, the random access procedure is of two types:

- Contention-based
- Contention free

3.2.1 Contention-free procedure:

Out of the 64 available preamble signatures some of them are reserved for contention-free random access so that different UEs do not use the same signature and hence here is no collision present in the procedure. This is useful when a quicker access to the eNodeB is required such as during handover from the current cell to another or eNodeB needs to send some new data in the downlink to the UE.

3.2.2 Contention-based procedure:

As the name indicates there is inherent risk of collision in this procedure i.e. multiple UEs may use the same preamble signature resulting in collision at the eNodeB.

The contention-based access procedure consists of the following steps:

1. Transmission of the preamble by the UE
2. Response of eNodeB for the preamble received.
3. L2/L3 message by the UE.
4. Contention resolution message the eNodeB.

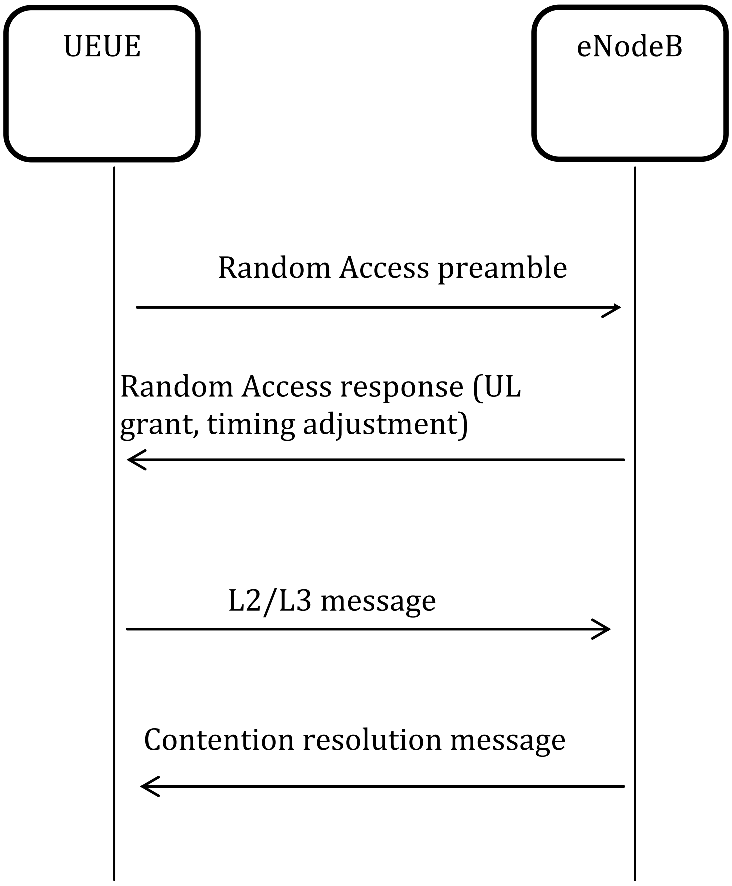


Figure 3.1 : Random Access Procedure

Step1: Preamble transmission by the UE:

Any UE that transmits the preamble initially selects a preamble signature from the available signatures (i.e. 64-signatures reserved for contention free access) and transmits it to the eNodeB. The broadcast system information indicates which preambles are available and also the frequency and time resources where the preamble has to be transmitted. The initial preamble transmission power at which the UE transmits is based on open-loop estimation with full compensation for path loss. This is designed to ensure that the received power at the eNodeB is independent of the path loss (Path loss is measured with the help of Downlink Reference Signal Received Power).

Step2: Random Access Response

The response by the eNodeB to the preamble that is transmitted by the UE is known as Random Access Response. It is transmitted on Physical Downlink Shared Channel (PDSCH).Random access response consists of the following:

- The detected preamble ID
- Timing adjustment.
- RA_RNTI (Radio Access Radio Network Temporary Identifier)-which indicated the frequency and time resources in which the preamble was detected.
- Temporary C-RNTI (Cell Radio Network Temporary Identifier)-This is assigned by the eNodeB to the UE. So all the UEs which transmit the same preamble receive the same temporary C-RNTI.

The response also consists of resource allocation message for the transmission of L2/L3 message by the UE. This is transmitted on Physical Downlink Control Channel (PDCCH).

If the UE does not receive the response message within the configure time window (usually 4ms window after 4ms from the transmission of the preamble) then the UE retransmits the preamble again.

Step3:Layer2/Layer3(L2/L3 message)

In the random access response message received by the UE it is indicated which resources are allocated for the transmission of its data. Based on the resources UE schedules its data to be transmitted on uplink using Physical Uplink Shared Channel (PUSCH). Along with the data the UE also transmits its identity. Since same resources have been allocated for all the UEs which transmit the same preamble in step1, there is a chance of collision at the eNodeB and thus no UE can be decoded correctly. The UEs restart the random access procedure once they reach the maximum number of HARQ(Hybrid Automatic Repeat reQuest) retransmissions.

Step 4: Contention Resolution Message

Contention resolution message uses HARQ. This message is addressed to the UE identity that is transmitted by it step3. So in case of a collision followed by successful decoding of L2/L3 message, the HARQ feedback is detected correctly on by the UE whose message has been detected while other UEs understand that collision has occurred and so they quickly exit the current random access procedure and start a new session of preamble transmission.

Location of PRACH:

PRACH is both time and frequency multiplexed with PUCCH and PUSCH. The time-frequency resources are allocated semi-statically by the eNodeB. They are provided resources within the PUSCH region and periodically repeated depending on factors such as the load in the current cell, number of active users etc.

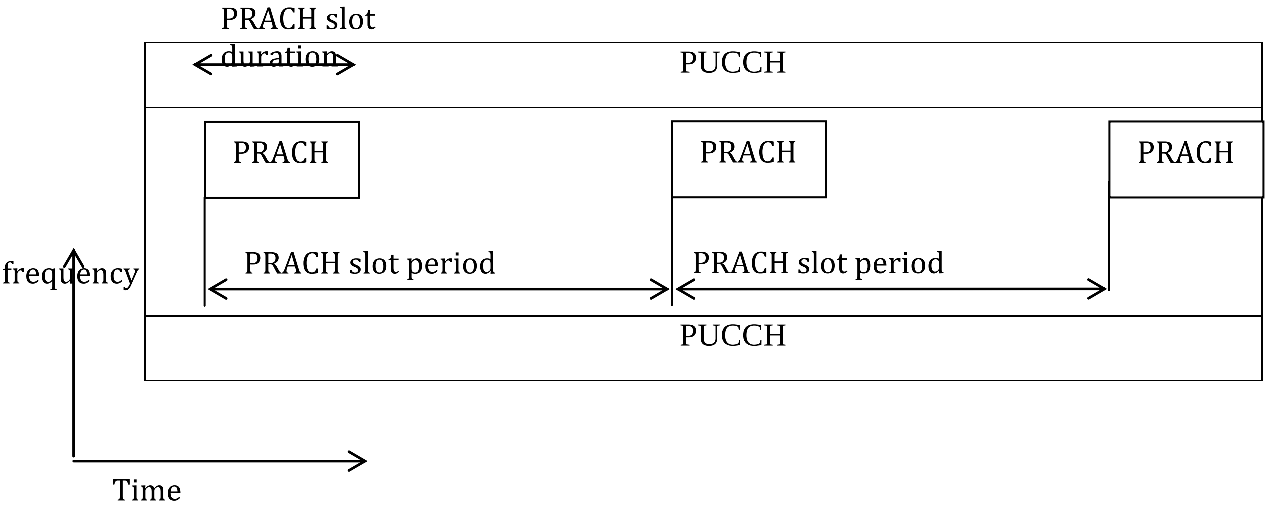


Figure 3.2 : Multiplexing of PRACH with PUSCH and PUCCH

Structure of RACH preamble:

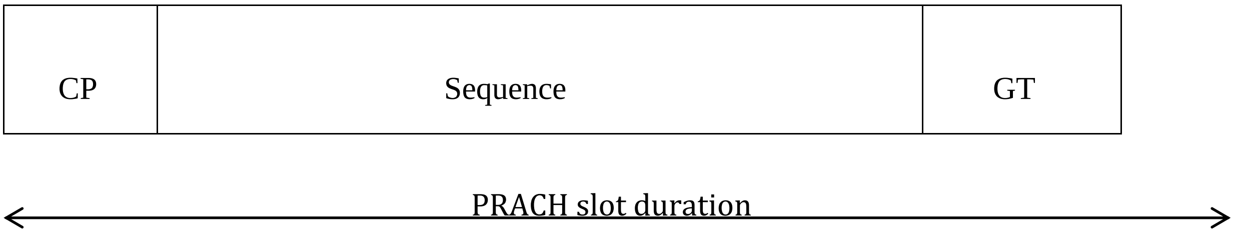


Figure 3.3 : Preamble structure

Here, sequence represents the preamble sequence that is being transmitted in the PRACH resource.

CP(Cyclic Prefix) :

The end portion of the preamble sequence is prefixed to the symbol. This portion of the symbol that is attached at the beginning of the symbol is known as the cyclic prefix. The amount of sequence that is copied depends on the delay spread of the channel. Cyclic Prefix serves two purposes. They are:

- It eliminates the inter symbol interference from previous symbol.
- When any symbol is passed through a channel linear convolution takes place. But with the addition of CP, it converts linear convolution to circular convolution which helps in a simple receiver design at eNodeB.

GT (Guard Time):

Some guard time is provided after the preamble sequence is transmitted. This is provided to accommodate any propagation delays so that the current symbol does not interfere with the data coming in the next slot.

Depending on the sequence and CP duration various types of PRACH formats are defined. These different lengths are available to support various cell sizes. The format that is being used in a cell is broadcasted with the help of System Information Block (SIB 2). So, the duration of PRACH symbol depends on the format that is chosen by the cell while the bandwidth allocated for its transmission is constant for all irrespective of the system bandwidth and it is equal to 1.08MHz (i.e.6 Resource Blocks). The sub-carrier spacing is 1.25 KHz which implies that there are 864 subcarriers in the available bandwidth. However only 839 subcarriers are used for the transmission of the PRACH sequence leaving 12.5 subcarriers on either side as guard subcarriers preventing interference from PUSCH data carrying sub-carriers.

Table 3.1: Random access preamble formats

Preamble Format	$T_{CP}\left(\mu s\right)$	$T_{SEQ}\left(\mu s\right)$	Typical usage
0	103.13	800	Normal 1 ms random access burst with 800 µs preamble sequence, for small to medium cells (up to ~14 km)
1	684.38	800	2 ms random access burst with 800 µs preamble sequence, for large cells (up to ~77 km) without a link budget problem
2	203.13	1600	2 ms random access burst with 1600 µs preamble sequence, for medium cells (up to ~29 km) supporting low data rates
3	684.38	1600	3 ms random access burst with 1600 µs preamble sequence, for very large cells (up to ~100 km)

Preamble sequence:

The following are the desirable aspects while choosing the form of sequence that is used for transmitting the preamble sequence. They are:

1. The sequence should minimise both inter-cell and intra-cell interference.
2. It should reduce the complexity at the receiver.
3. It should support high speed UEs.
4. It should be robust and detected even at low SNR values (especially for the cell-edge users).
5. It should require minimum transmission power.

The sequence that is chosen by LTE standard to meet all these requirements to the possible extent is ZC sequence.

3.3: Zadoff-Chu(ZC)-sequence:

These sequences derived the name from their inventors Solomon A. Zadoff and D. C. Chu. In general ZC sequence is given by:

$$x_u(n) = \exp[-j\frac{\pi un(n+1)}{N_{ZC}}] \quad ; \quad 0 \le n \le N_{ZC} - 1$$

Where u= ZC sequence index.

N_{ZC} =sequence length (it is equal to 839 in LTE)

The following are the properties of the ZC sequences:

1. A ZC sequence has constant amplitude, and its N_{ZC} -point DFT also has constant amplitude. The constant amplitude property limits the Peak-to-Average Power Ratio
(PAPR) and generates bounded and time-flat interference to other users. It also simplifies the implementation as only phases need to be stored and computed but not amplitudes.
2. Auto-correlation property: ZC sequences of any length when correlated with the cyclic shifts of the same sequence it results in a delta function(i.e. they have ideal cyclic auto-correlation property). Mathematically:

   $$r_{kk}(\alpha) = \sum_{n=0}^{N_{ZC}-1} x_u(n) x_u(n+\alpha) = \delta(\alpha)$$

   Where $r_{kk}(\alpha)$ is the periodic autocorrelation of sequence x_u at a lag 'α'. So,

   $r_{kk}(\alpha) =$ 0, α =0 and

   $r_{kk}(\alpha) \neq 0$, $\alpha \neq 0$.

3. Cross-Correlation property: ZC sequences have good cyclic cross correlation property. The absolute value of the cyclic cross-correlation function between any two ZC sequences is constant and equal to $1/\sqrt{\text{Nzc}}$ if |q1 − q2| (where q1 and q2 are the sequence indices) is relatively prime with respect to Nzc (a condition that can be easily guaranteed if Nzc is a prime number).

The PRACH preamble that is transmitted is given by:

$$s\left(t\right)=\beta_{PRACH}\sum_{k=0}^{N_{ZC}-1}\sum_{n=0}^{N_{ZC}-1}x_{u,v}\left(n\right).\exp\left[j\frac{2\pi nk}{N_{zc}}\right]*\exp\left[j2\pi\left[k+\varphi+a\left(k_0+0.5\right)\right]\Delta f_{RA}\left(t-T_{CP}\right)\right]$$

$$,\quad 0\le t\le T_{SEQ}+T_{CP}$$

Where:

- β_{PRACH} is the amplitude scaling factor
- $k_0 = n_{PRB}^{RA}N_{SC-}^{RB} - N_{RB}^{UL}N_{SC}^{RB} / 2$ .The location in the frequency domain is controlled by the parameter n_{PRB}^{RA}, expressed as an RB number configured by higher layers and fulfilling $0 \le n_{PRB}^{RA} \le N_{RB}^{UL} - 6$.
- The factor $a = \Delta f / \Delta f_{RA}$ accounts for the ratio of subcarrier spacing between the PUSCH and PRACH.
- φ defines a fixed offset determining the frequency-domain location of the random access preamble within the RBs.
- N_{RB}^{UL} =uplink system bandwidth(in RBs)
- N_{SC}^{RB} =number of subcarriers per RB (=12).

3.4 Implementation of PRACH:

3.4.1 Transmitter:

At the transmitter, the preamble to be transmitted is selected from the available signatures that are broadcasted by the eNodeB using broadcast signalling. The transmitter structure is as follows:

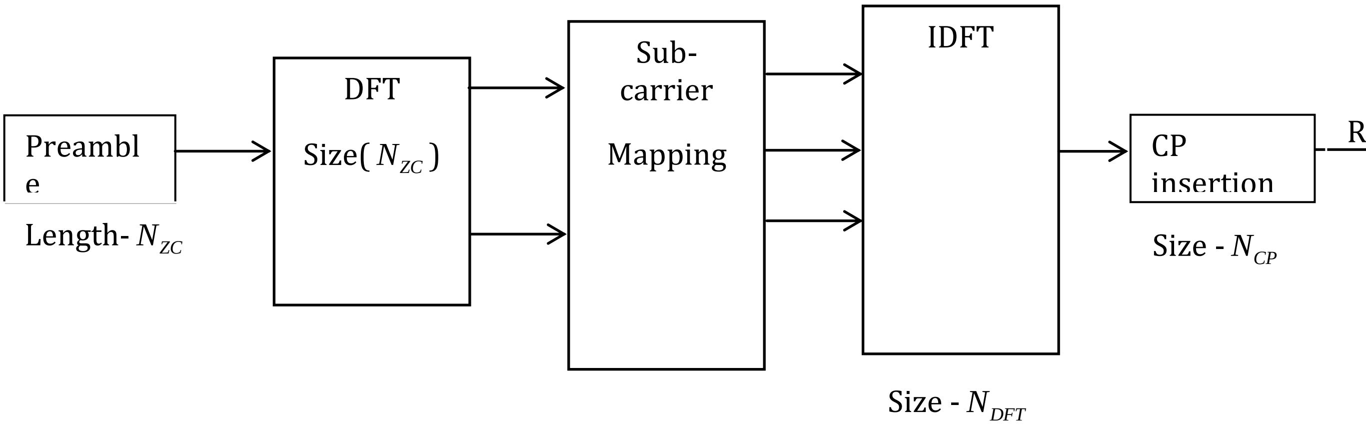


Figure 3.4: PRACH transmitter

The preamble initially is assumed to be in frequency domain. In LTE, the multicarrier technique that is used for the transmission from the UE is SC-FDMA. SC-FDMA is used instead of OFDMA in order to overcome the PAPR problem. But in the case of transmission of PRACH preamble there is no need to explicitly use an extra DFT block due to the constant amplitude property of the ZC sequence. So the preamble is directly converted into time domain with the help of the IDFT block. The size of the IDFT that is to be used depends on the bandwidth of the system. In case if 20MHz is the bandwidth then an IDFT size of 24,576 is to be used which is hard to realize in practice. In that case instead of going for such a large IDFT we go for smaller IDFT followed by shifting the preamble to the required frequency location through time-domain upsampling and then filtering. This is followed by CP insertion and then the resulting sequence is transmitted to the eNodeB after converting it into a RF signal.

3.4.2 PRACH Receiver

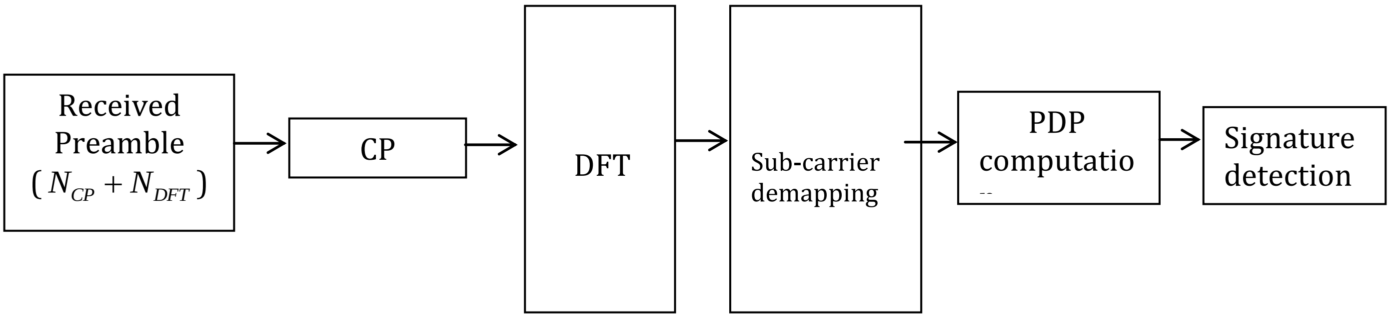


Figure 3.5 : PRACH Receiver

The receiver's main task is to identify the preamble signature that has been transmitted by the UE. The following steps are involved in the detection of the preamble. They are removal of the CP, transforming the time domain samples into frequency domain, sub-carrier de-mapping, power delay profile computation and finally signature detection.

Power Delay Profile calculation:

The power delay profile of the received preamble sequence is given by :

$$w(l)=\left|z_q(l)\right|^2=\left|\sum_{n=0}^{N_{ZC}-1} y(n)x_q^*\left[(n+l)_{N_{ZC}}\right]\right|^2$$

Where:

$w(l)$=Power Delay Profile at a lag 'l'.

$z_q(l)$=discrete periodic correlation function

$y(n)$=received sequence.

$x(n)$ =reference ZC sequence.

Using the properties of DFT the periodic correlation of the sequence can be efficiently carried out in the frequency domain as:

$$z_q(n) = IDFT\left[Z_q(k)\right]_n \quad \text{For n=0,1,2…..} N_{ZC} - 1.$$

Where

$$Z_q(k) = Y(k)X_q^*(k) \quad \text{For k=0,1,2…..} N_{ZC} - 1.$$

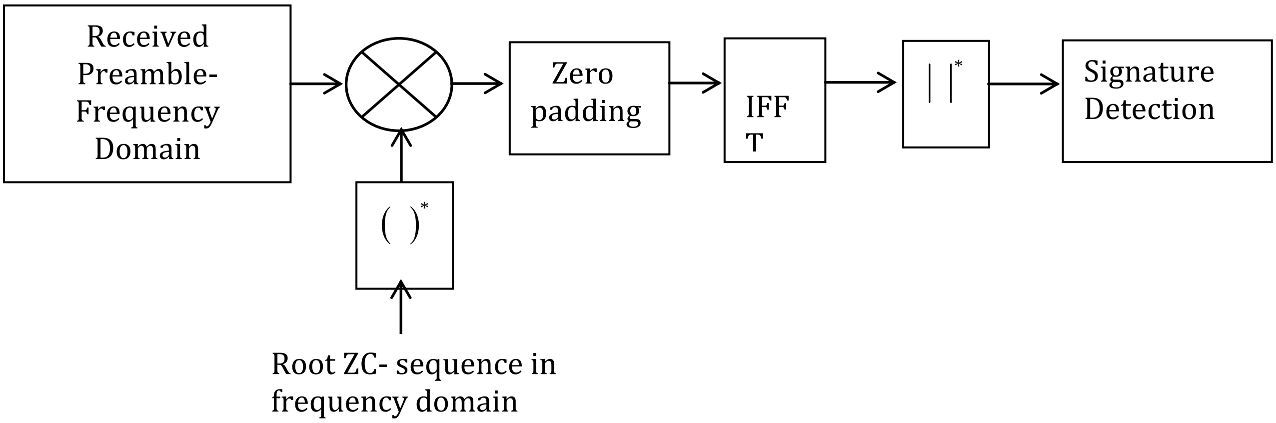


Figure 3.6 : Power Delay Profile computation

Signature Detection:

The power delay profile needs to be calculated for various reference preamble sequences, but as all the reference sequences are generated form the cyclic shifts of the same sequence, the frequency domain computation of the Power delay profile of the root sequence provides the concatenated PDPs of all root sequences. After the computation of the PDP, the next task is the detection of the peak (with the help of detection threshold) and ensure that it is present in the desired window and thus calculate the time adjustment.

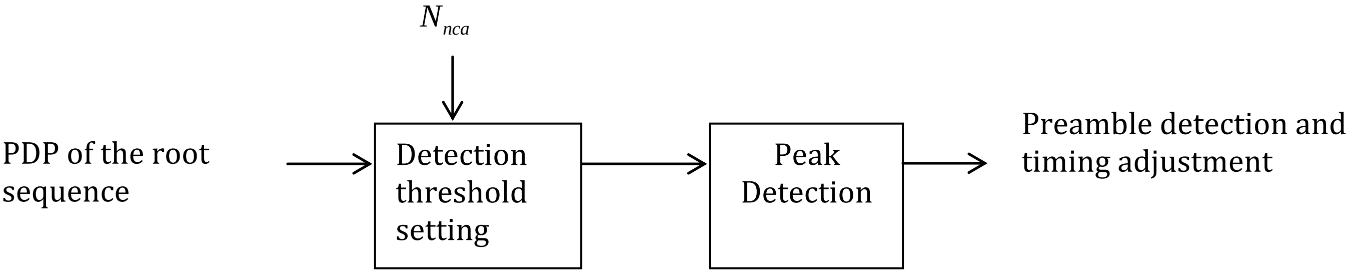


Figure 3.7: Signature detector structure

Detection threshold:

The setting up of the threshold in the detection of the peak of the power delay profile is carried out by observing the noise variance at the receiver in the absence of the preamble transmission. Let us assume that the signal that is received in the absence of the transmitted preamble is given by $g_m(n)$ where m denotes the m^{th} non-coherent interferer. Hence the total noise power that is observed is given by :

$$d(\tau) = \sum_{m} \sum_{k=0}^{N_{ZC}-1} \left| g_m(k) \right|^2$$

where: m= indicates the m^{th} interferer

The detection threshold is set as follows:

$$\alpha_\tau = \frac{1}{N_{ZC}} \left(d(\tau) \right)$$

.

The peak can thus be identified and hence the corresponding sequence that has been transmitted by the user. Upon detection of the peak within the search window, timing adjustment command is transmitted by the eNodeB indicating the UE to adjust its timing and thus achieve the timing synchronization in the uplink.

Chapter-4

PUCCH(Physical Uplink Control Channel)

4.1 Introduction:

The physical channel present in LTE which is used for the transmission of Uplink Control Information (UCI) is PUCCH. The signals that are transmitted on this channel are transmitted independently with respect to the uplink data. The UCI may consist of

1. Scheduling Requests (SRs): These are transmitted by the UE whenever it requires uplink resources for the transmission of its data packets.
2. Hybrid ARQs: These are transmitted by the UE in response to the data packets it received in the downlink. ACK (Acknowledgment) is sent in case of error free reception of the downlink data else Negative acknowledgement (NACK) is sent.
3. Channel State Information (CSI): CSI consists of
    - Channel Quality Indicator (CQI)
    - MIMO related feedback such as Rank Indicator (RI) and Precoding Matrix Indicator (PMI).

The amount of UCI (Uplink Control Information) a UE can transmit in a subframe depends on the number of SC-FDMA symbols available for transmission of control signalling data. Depending on the control information to be transmitted various formats are supported on PUCCH.

Table 4.1: PUCCH formats

PUCCH Format	Uplink Control Information
1a	1-bit HARQ ACK/NACK with/without Scheduling Request(SR)
1b	2-bit HARQ ACK/NACK with/without SR
2	Channel State Information(CSI)
2a	CSI and 1-bit HARQ ACK/NACK
2b	CSI and 2-bit HARQ ACK/NACK

4.2 Location of PUCCH :

4.2.1 Time-domain resources:

The time domain resources for PUCCH transmission are allocated by the eNodeB dynamically depending on the resources that are available after allocating for the transmission of the uplink shared data channel. One PUCCH region lasts for one subframe.

4.2.2 Frequency-domain resources:

The control signalling on the PUCCH is transmitted in a frequency region that is normally configured to be on the edges of the system bandwidth. Positioning the control regions at the edges of the system bandwidth has a number of advantages, including the following:

1. The frequency diversity achieved through frequency hopping is maximized by allowing hopping from one edge of the band to the other.
2. Out-Of-Band (OOB) emissions are smaller if a UE is only transmitting on a single RB per slot compared to multiple RBs. The PUCCH regions can serve as a kind of guard band between the wider-bandwidth PUSCH transmissions of adjacent carriers and can therefore improve coexistence .
3. Using control regions on the band edges maximizes the achievable PUSCH data rate,as the entire central portion of the band can be allocated to a single UE. If the control regions were in the central portion of a carrier, a UE bandwidth allocation would be limited to one side of the control region in order to maintain the single-carrier nature of the signal, thus limiting the maximum achievable data rate.
4. Control regions on the band edges impose fewer constraints on the uplink data scheduling, both with and without inter-/intra-subframe frequency hopping.

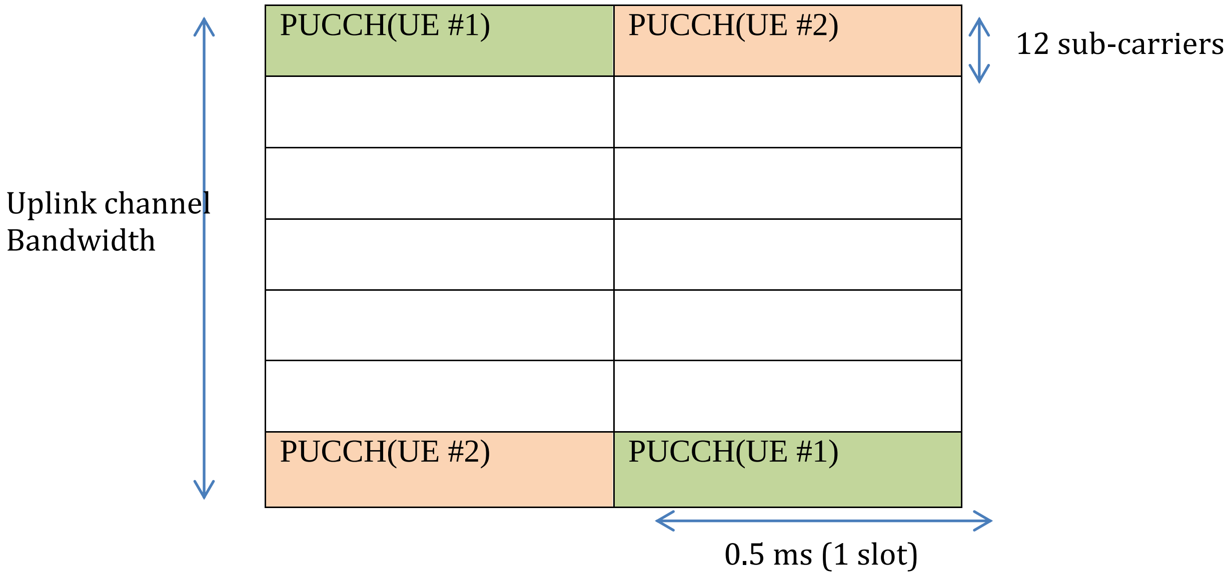
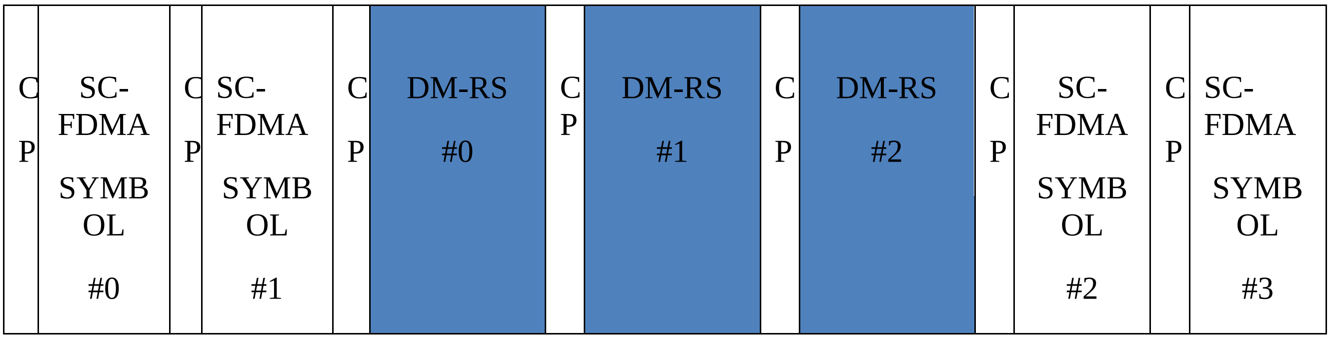


Figure 4.1: PUCCH resource allocation

4.3 Physical Uplink Control Channel (PUCCH) Structure:

The PUCCH slot structure for:

1) Format 1a/1b:

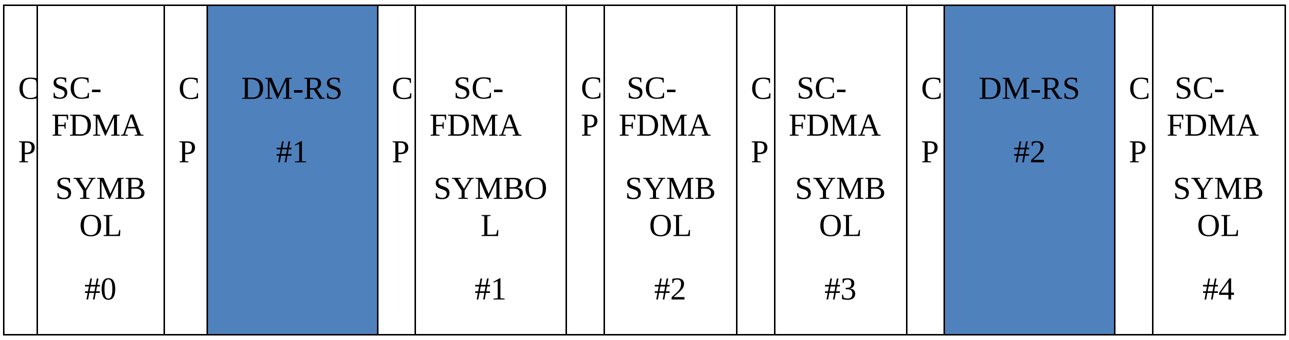


CP	SC-FDMA SYMBOL #0	CP	SC-FDMA SYMBOL #1	CP	DM-RS #0	CP	DM-RS #1	CP	DM-RS #2	CP	SC-FDMA SYMBOL #2	CP	SC-FDMA SYMBOL #3

Figure 4.2 : PUCCH format 1a

The control data is transmitted in SC-FDMA symbols 0,1,5,6 in the slot and the reference symbols are transmitted in SC-FDMA symbols 3,4,5.

2) Format 2/2a/2b:



CP	SC-FDMA SYMBOL #0	CP	DM-RS #1	CP	SC-FDMA SYMBOL #1	CP	SC-FDMA SYMBOL #2	CP	SC-FDMA SYMBOL #3	CP	DM-RS #2	CP	SC-FDMA SYMBOL #4

Figure 4.3: PUCCH format 1b

The control data is transmitted in SC-FDMA symbols 0, 2,3,4,6 in the slot and the reference symbols are transmitted in SC-FDMA symbols 1, 5.

Desirable characteristics of DM-RS:

- Constant amplitude in the frequency domain for equal excitation of all the allocated subcarriers for unbiased channel estimates.
- Good autocorrelation properties for accurate channel estimation.
- Good cross-correlation properties between different RSs to reduce interference from RSs transmitted on the same resources in other cells.

These characteristics are satisfied by Zadoff-Chu sequences. Hence ZC sequences are used as demodulation reference signals in the transmission of PUCCH.

4.4 Transmission scheme:

1) Format 1a/1b

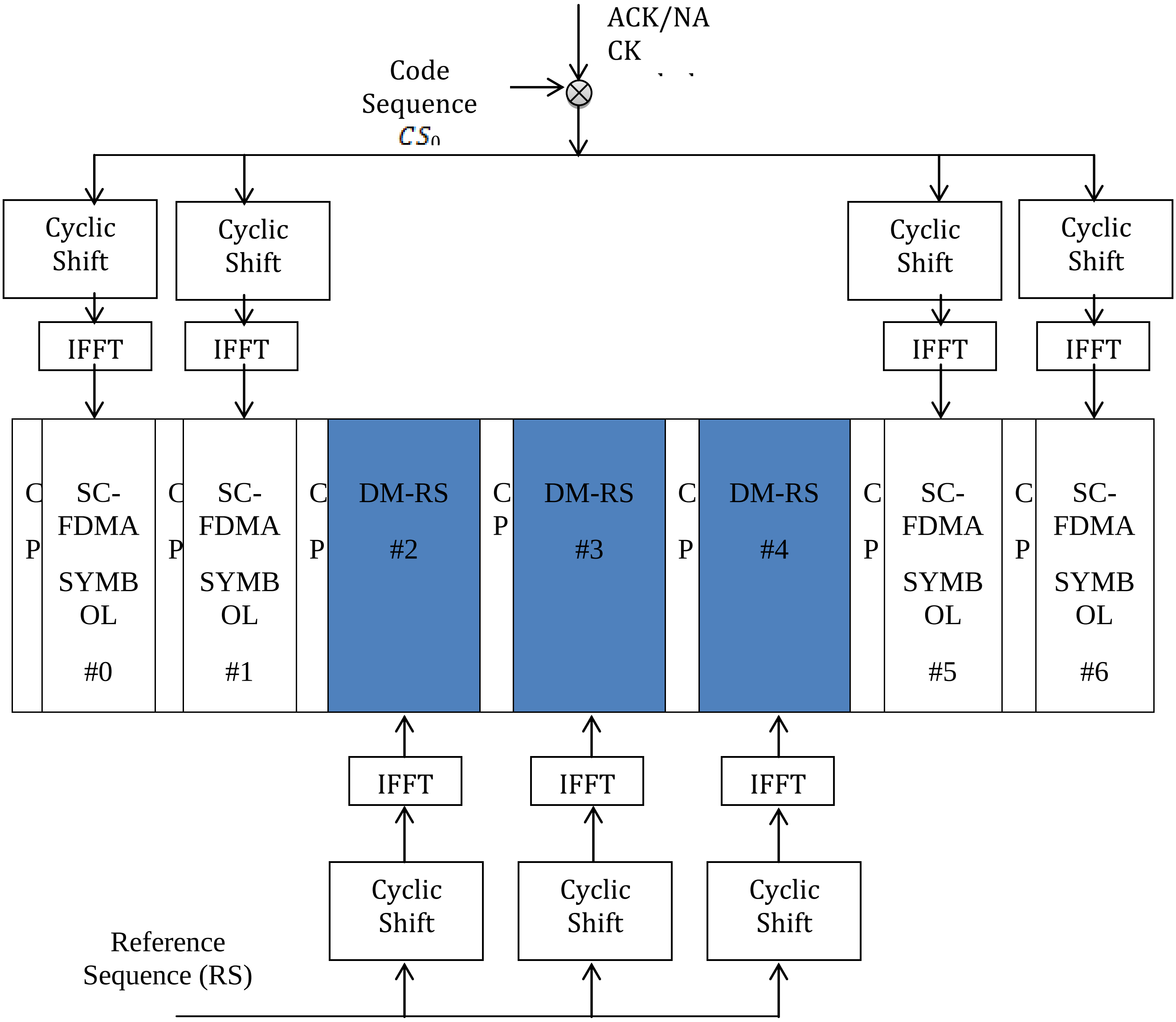


Figure 4.4 : Transmission scheme for format 1a

The ACK/NACK that is sent by the UE is multiplied by different cyclic shifts of the given code word and then transmitted through SC-FDMA symbols 0,1,5,6 along with DeModulation-Reference Signals (DM-RS) transmitted on symbols 2, 3, 4 for coherent detection of the transmitted data at the eNode.

Format 2/2a/2b:

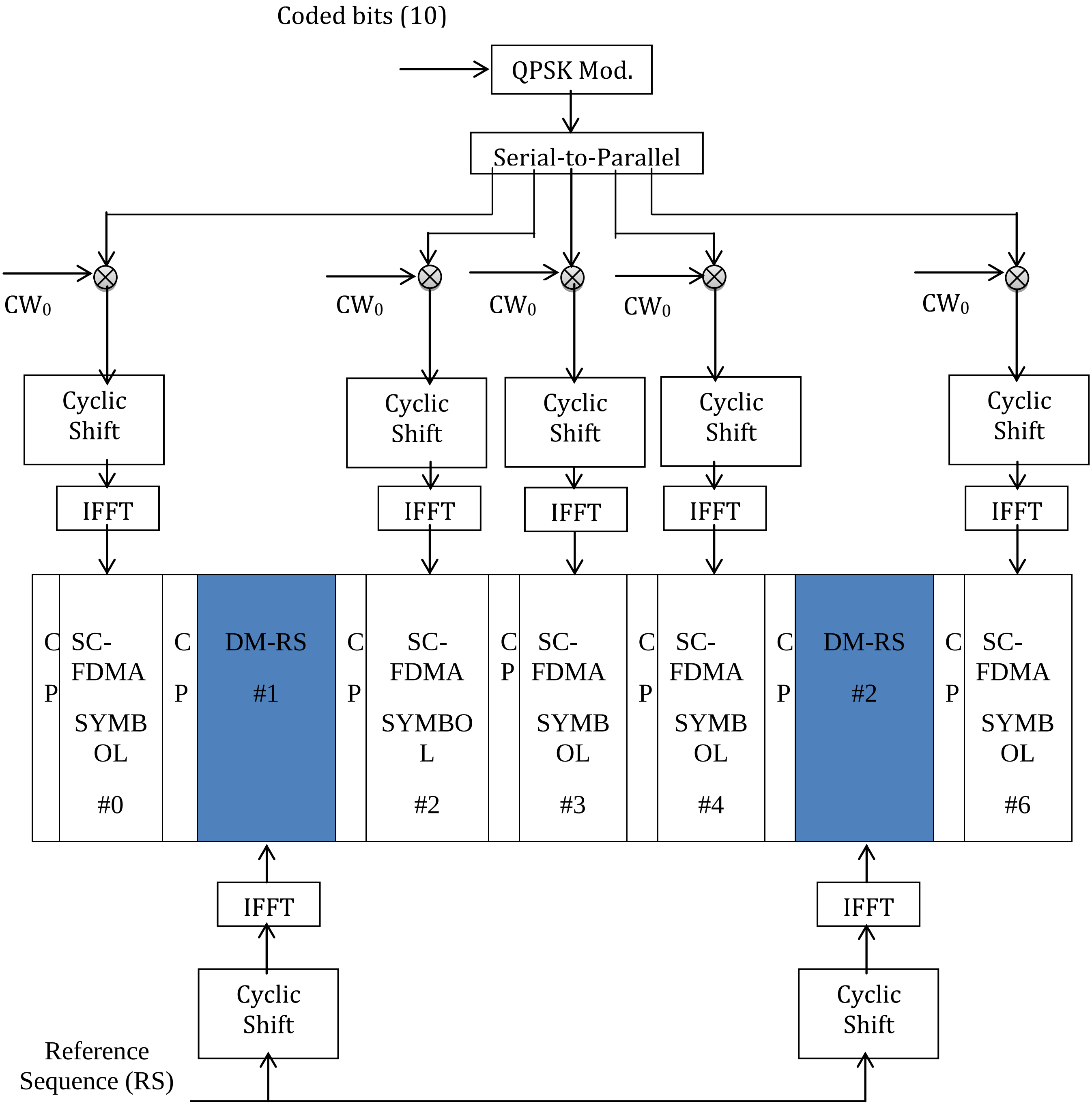


Figure 4.5 : Transmission scheme for format 1b

The CSI(10 coded bits) that are sent by the UE is first mapped(QPSK)and then five output symbols are multiplied by different cyclic shifts of the given code word and then transmitted through SC-FDMA symbols 0,2,3,4,6 along with DeModulation-Reference Signals(DM-RS) transmitted on symbols 1,5 for coherent detection of the transmitted data at the eNodeB.

4.5 PUCCH Receiver Algorithm:

Receiver structure:

The following steps are involved in the detection of PUCCH symbols.

1. Channel Estimation
2. Equalization
3. Code matched filtering.

Schematic of the receiver:

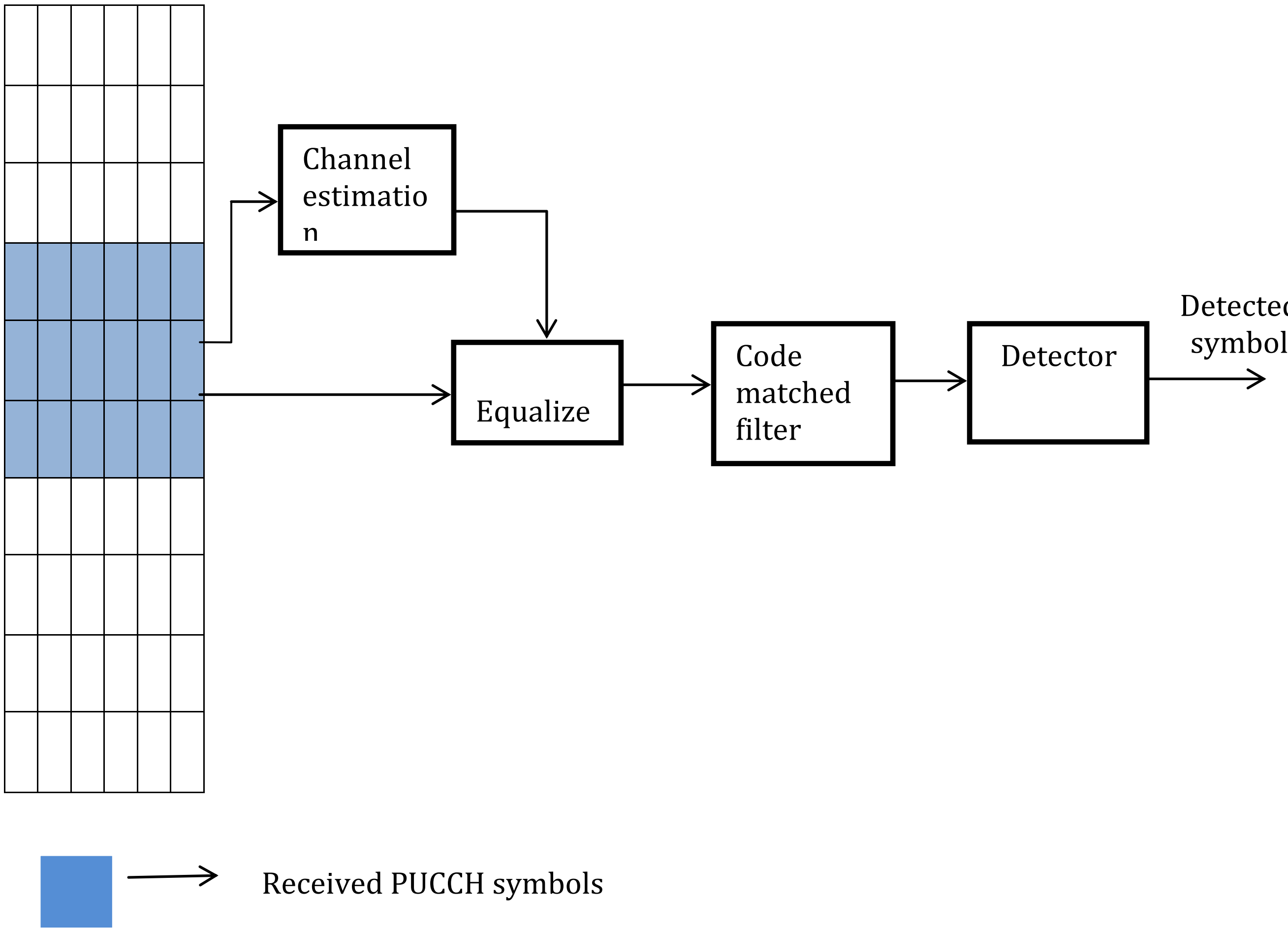


Figure 4.6 : PUCCH Receiver Structure

Let the control data that is transmitted by user ‘j’ be denoted by dj and let the code word that is used for the transmission at subcarrier by user ‘j’ be frequency ‘k’ be denoted by Ck,j. The received PUCCH symbol is given as:

$$y_k = \begin{pmatrix} y_{k,1} \\ y_{k,2} \\ \cdot \\ \cdot \\ y_{k,N_R} \end{pmatrix} = \sum_{j=1}^{M} Hc_{k,j} d_j + n_k$$

Where: NR represents number of antennas at the receiver.

H is a NR * 1 matrix.

Consider the symbol received at antenna ‘l’ $1 \le l \le N_R$

The primary goal of processing the received PUCCH signal is to extract the symbol dj that is transmitted by user ‘j’. It can be observed that in order to extract the transmitted control data we need to mitigate the effect of channel and also the interference from the remaining users. The channel can be estimated with the help of the reference symbols that have been transmitted through the OFDM symbols 2, 3, 4, in a given slot for format 1a/1b and with the help of OFDM symbols 1,6 in case of format 2/2a/2b.

1) Channel Estimation

The technique that is used for the estimation of the channel is 2D-MMSE channel estimation (2-Dimensional Minimum Mean Square Estimation).

$$y_p(m,k) = x_p(m,k) * h(m,k) + n(m,k)$$

Where: m =OFDM symbol index

k=subcarrier frequency index

h=channel

x_p=transmitted pilot symbol

y_p=received pilot symbol

The signal model for the estimation of the channel is as follows:

a) For format 1a/1b:

$$\begin{pmatrix} y_p(2,0) \\ y_p(2,1) \\ \cdot \\ y_p(2,k-1) \\ y_p(3,0) \\ y_p(3,1) \\ \cdot \\ y_p(3,k-1) \\ y_p(4,0) \\ y_p(4,1) \\ \cdot \\ y_p(4,k-1) \end{pmatrix} = \begin{pmatrix} x_p(2,0) & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & x_p(2,1) & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & x_p(2,k-1) & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & x_p(3,0) & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & x_p(3,1) & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & x_p(3,k-1) & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & x_p(4,0) & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & x_p(4,1) & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & x_p(4,k-1) \end{pmatrix} \begin{pmatrix} h_p(2,0) \\ h_p(2,1) \\ \cdot \\ h_p(2,k-1) \\ h_p(3,0) \\ h_p(3,1) \\ \cdot \\ h_p(3,k-1) \\ h_p(4,0) \\ h_p(4,1) \\ \cdot \\ h_p(4,k-1) \end{pmatrix} + \begin{pmatrix} n(2,0) \\ n(2,1) \\ \cdot \\ n(2,k-1) \\ n(3,0) \\ n(3,1) \\ \cdot \\ n(3,k-1) \\ n(4,0) \\ n(4,1) \\ \cdot \\ n(4,k-1) \end{pmatrix}$$

b) For format 2/2a/2b:

$$\begin{pmatrix} y_p(1,0) \\ y_p(1,1) \\ \cdot \\ y_p(1,k-1) \\ y_p(5,0) \\ \cdot \\ \cdot \\ \cdot \\ y_p(5,k-1) \end{pmatrix} = \begin{pmatrix} x_p(1,0) & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & x_p(1,1) & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & x_p(1,k-1) & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot\ \ \cdot & \cdot & \cdot & \cdot & x_p(5,0) & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & x_p(5,k-2) & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & x_p(5,k-1) \end{pmatrix} \begin{pmatrix} h(1,0) \\ h(1,1) \\ \cdot \\ h(1,k-1) \\ h(5,0) \\ \cdot \\ \cdot \\ \cdot \\ h(5,k-1) \end{pmatrix} + \begin{pmatrix} n(1,0) \\ n(1,1) \\ \cdot \\ n(1,k- \\ n(5,0) \\ \cdot \\ \cdot \\ \cdot \\ n(5,k- \end{pmatrix}$$

The channel over the entire slot is calculated using the 2-D MMSE channel estimation technique as follows:

Estimate h (m,k) all over the grid using y_p, x_p and channel statistics

$$\hat{h} = \left(\hat{h}(0,0) \quad \hat{h}(0,1) \quad \ldots \quad \hat{h}(1,0) \quad \hat{h}(1,1) \quad \ldots \quad \hat{h}(M-2,K-2) \quad \hat{h}(M-1,K-1)\right)^T$$

Corresponding equations are:

$$\hat{h} = wy_p$$

Where: yp = received pilot symbol

W = weights of MMSE estimator

The weights are given by:

$$w = R_{hy_p} R_{y_p y_p}^{-1}$$

Where:

$$R_{hy_p} = E(hy_p^H) = R_{hh_p} X^H$$

$$R_{y_p y_p} = E(y_p y_p^H) = XR_{h_p h_p} X^H + R_{nn}$$

$$R_{nn} = (N_0 + \sum P_i)I$$

Given: P_i is the power of the ith interferer

$$R_{hh} = E\left[h(m_i, k_j)h^*(m_q, k_r)\right] = R_T\left[\left(m_q - k_r\right)T_{sym}\right]R_f\left[(k_r - k_j)F_{sub}\right]$$

Where:

$$R_T(\Delta t) = \sin c(2 f_d \Delta t)$$

$$R_f(\Delta f) = \sin c(\tau_{\max}\Delta f)\exp(-j\pi\tau_{\max}\Delta f)$$

From the above technique the channel for the entire grid has been estimated. Our next goal is to mitigate the effects of the channel and also interference. This is done with the help of MMSE equalization.

2) MMSE Equalization :

The output of the MMSE equalizer output is given by:

$$z_{k,j} = w_j y_k$$

Where: w_j is the weight of equalizer applied to ‘j’th user and is given by

$$w_j = h_{k,j}^{+} R_{i+n}^{-1}$$

$$R_{i+n} = \sum_{j=1}^{M} h_{k,j} h_{k,j}^{+} \sigma_c^{\ 2} + R_{nn}$$

Where: R_{nn} is the covariance matrix of the noise.

The equalized symbol is then transmitted through the code matched filter to detect the actual symbol transmitted.

3) Code Matched Filter:

The principle behind code matched filter is as follows:

If C_0 and C_1 be the two orthogonal code sequences of code length N, then

$$\sum_i C_0(i) C_1(i) = 0$$ Where i =0, 1… N-1

Applying the same principle

$$\sum_i C_{k,j}(i) C_{k,m}(i) = 0$$ for $j \neq m$.

Where $C_{k,j}$ is the code word used by user j and $C_{k,m}$ is the code word used by user m.

The equalized symbol is applied to code matched filter and the output is given as:

$$d_j = \frac{1}{N} \sum_{k=1}^{N} c_{k,j}^{*} z_{k,j}$$

Where: N is the total number of subcarriers.

$\hat{d}_j$ is the detected symbol that has been transmitted by user ‘j’.

Chapter-5

Results and Conclusions

1. PRACH representation in a sub-frame.

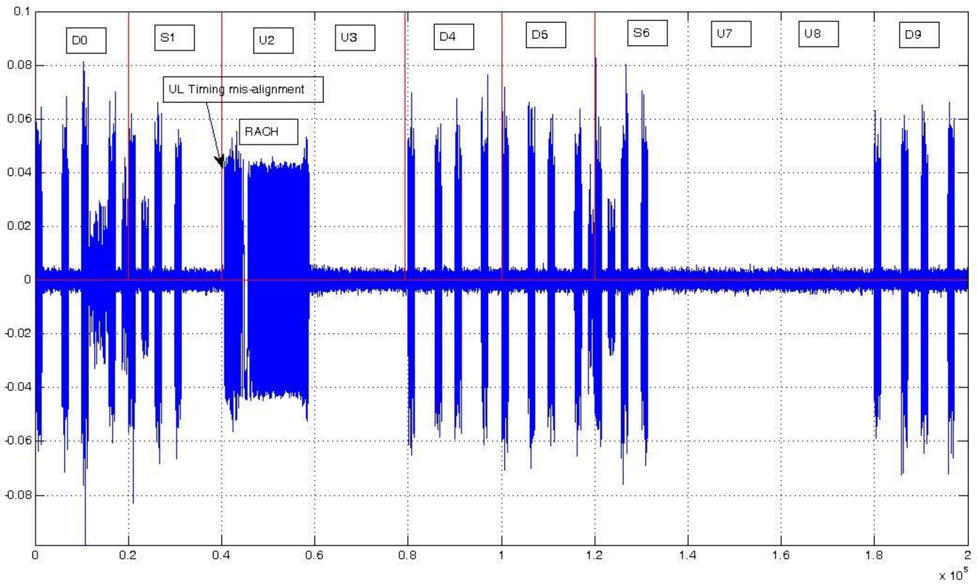


Figure 5.1 : PRACH Representation

2. Generated PRACH preamble with different root indices:

- Root index=0

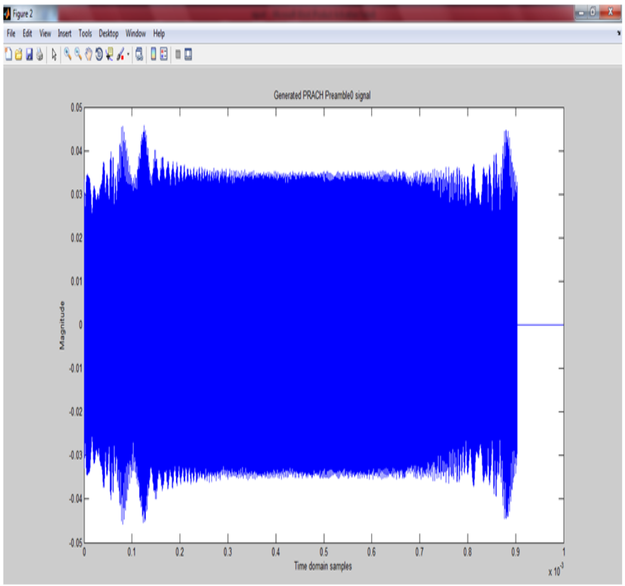


Figure 5.2 : preamble with root index 0

- Root index=5

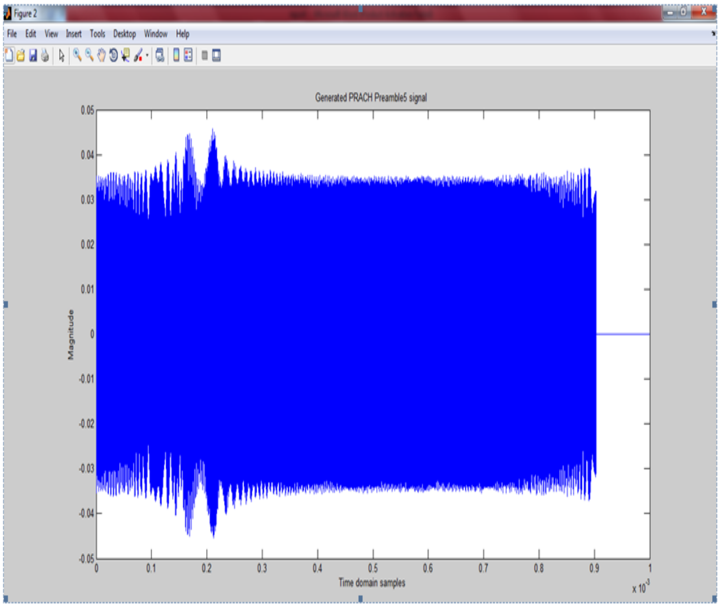


Figure 5.3 : preamble with root index 5

3. Detection of multiple UEs in real time environment using MW-1000 test bed

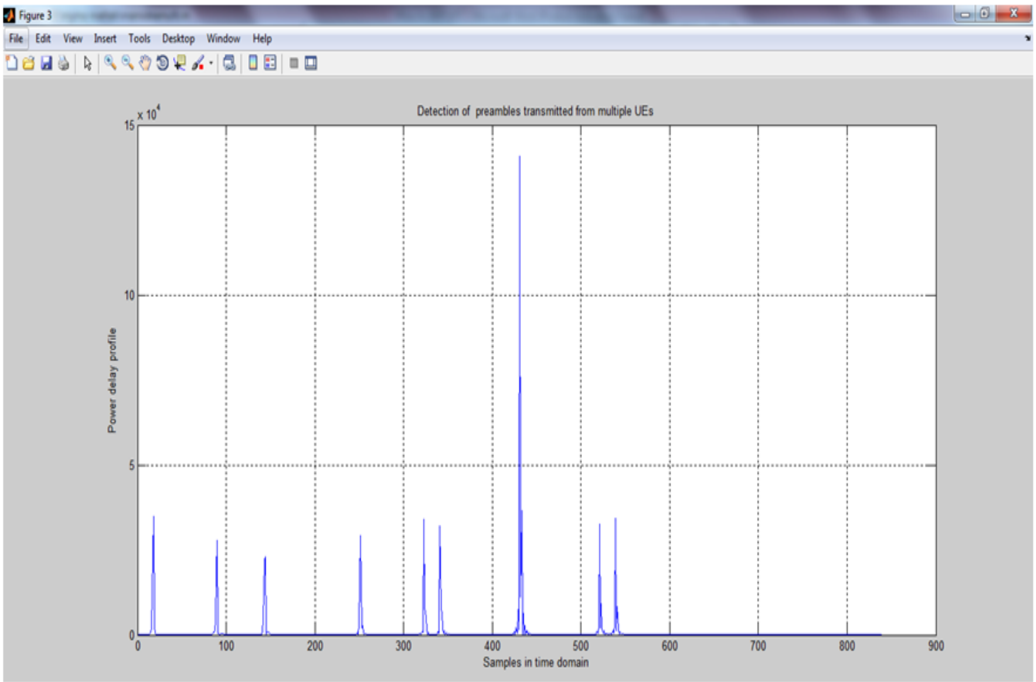


Figure 5.4: Multiple UE detection

4. BER Vs SINR curve for PUCCH format 1b

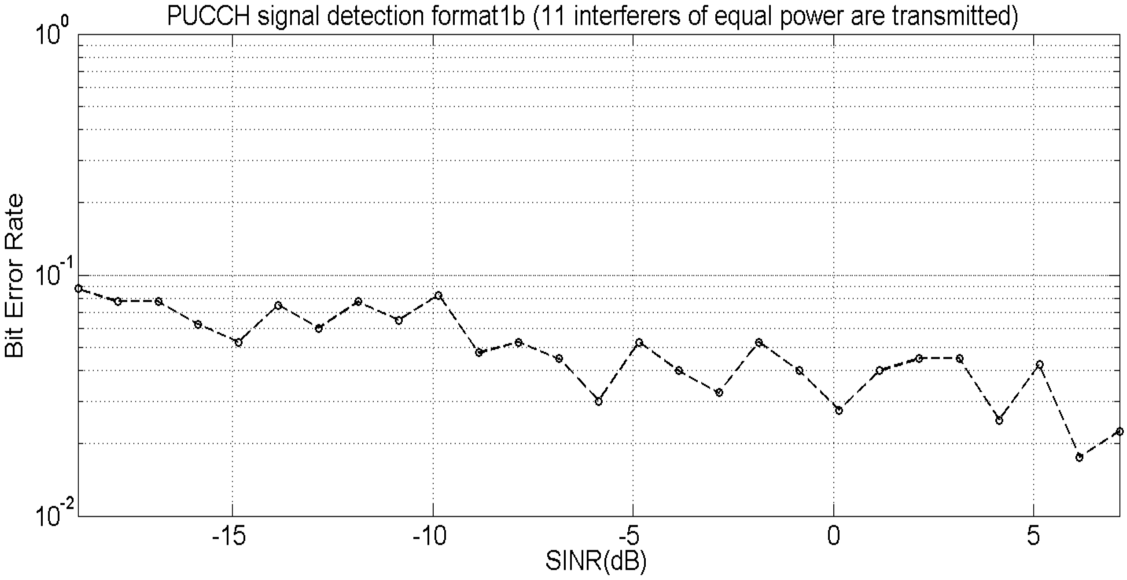


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Figure 5.5 :BER Vs SINR for format 1b

5. Format 1b constellation diagram

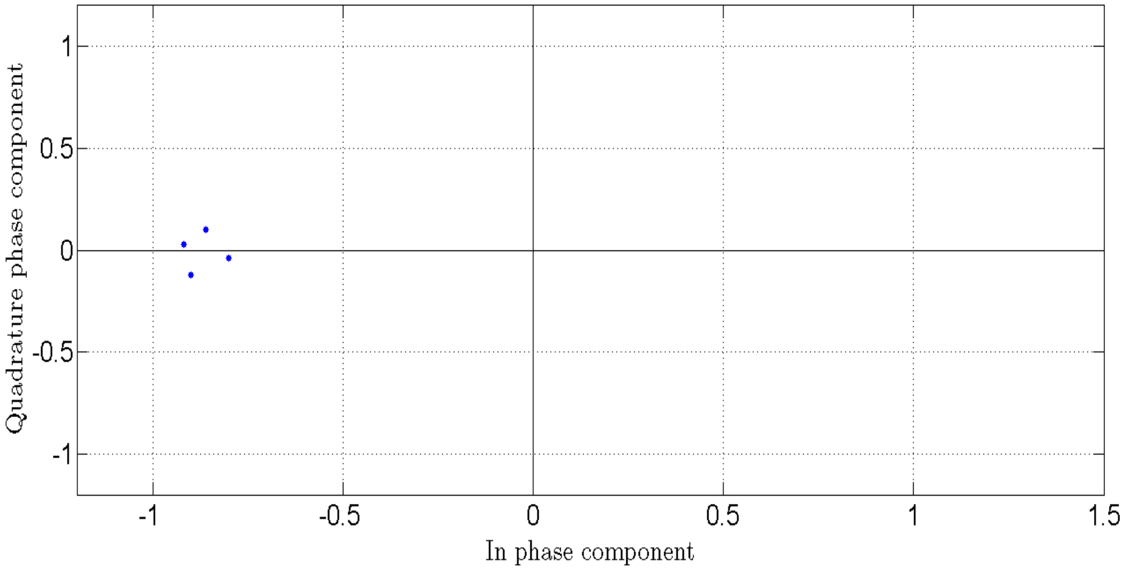


Figure 5.6 :Constellation diagram for format 1b

6. BER Vs. SINR curve for PUCCH format 1a

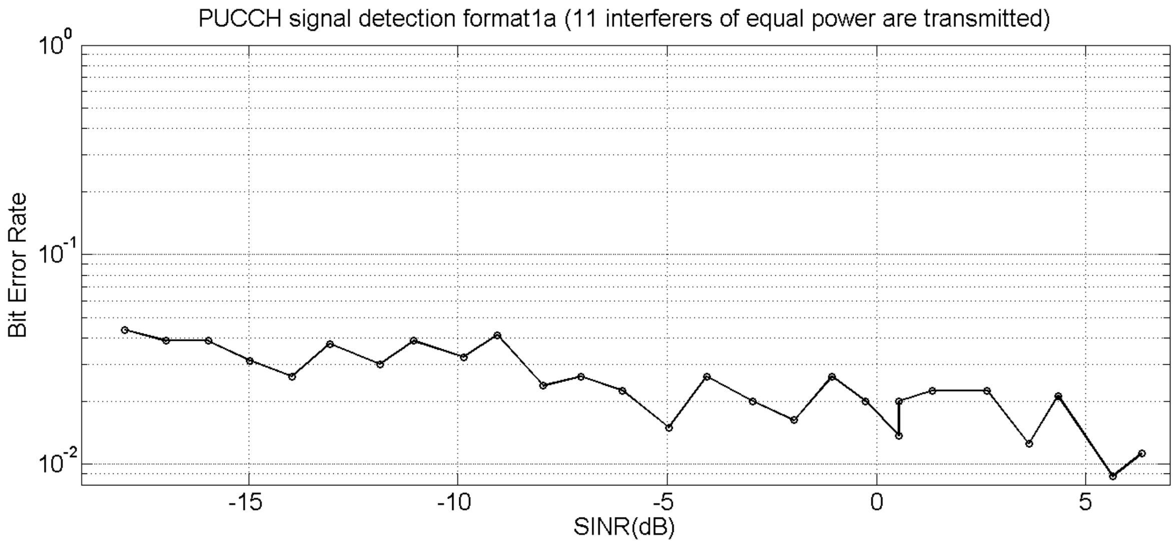


Figure 5.7 :BER Vs SINR for format 1a

7. Format 1a constellation diagram

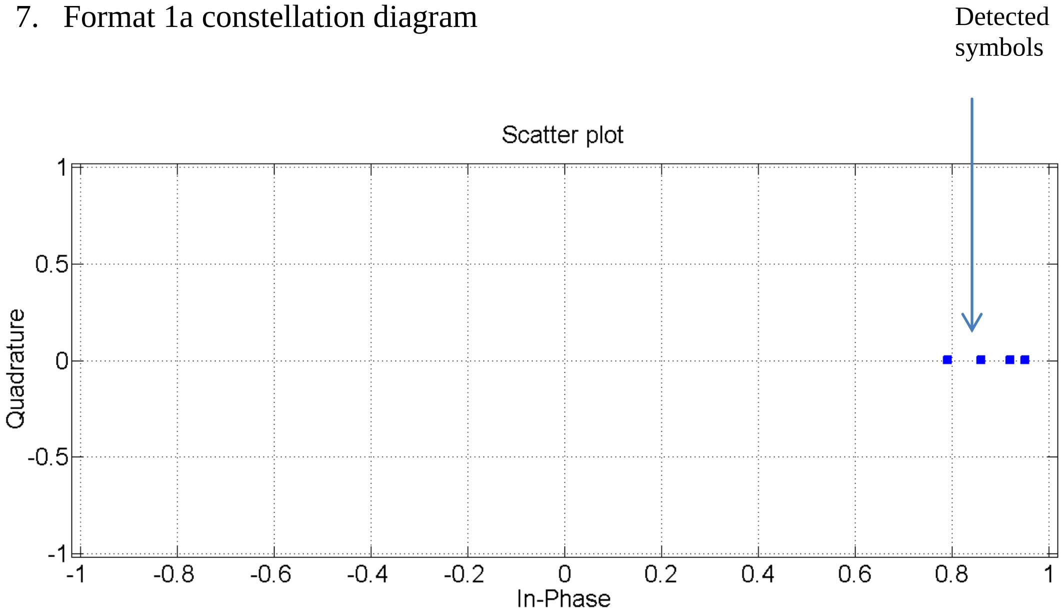
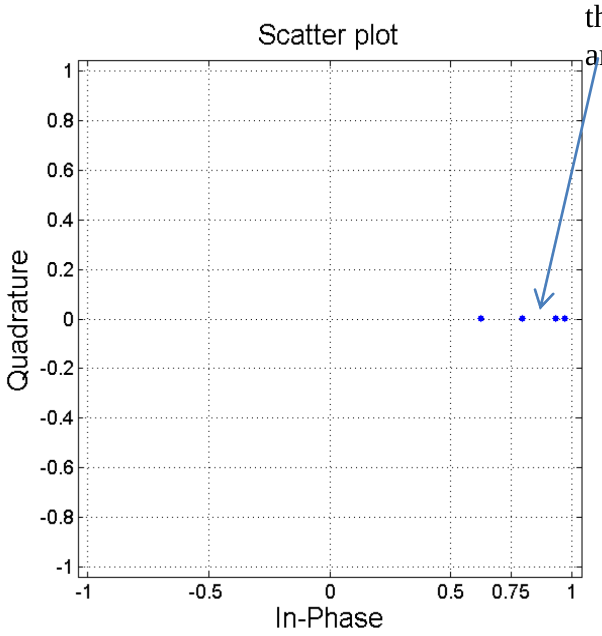


Figure 5.8:Constellation diagram for format 1a

8. Constellation diagram:

Representing detected symbols in real time



Detected control symbol transmitted by the UE in real time implying that the symbol transmitted is an ACK

Figure 5.5 :Real time detected symbols for format 1a

Conclusions:

Uplink timing synchronization that is essential for the establishment of connection UE and eNodeB is achieved with the help of PRACH and multiple UEs have been successfully detected in real time environment. Also the control information that has been transmitted by the UE using PUCCH has been detected successfully for formats 1a,1b in real time environment.

The detection probability can further be increased by using MIMO techniques and can be extended to other PUCCH formats also.

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