INITIAL CELL SITE SYNCHRONIZATION IN LTE SYSTEM

A Thesis

Presented to the

Faculty of

San Diego State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

in

Electrical Engineering

by

Parag Kothari

Fall 2013
SAN DIEGO STATE UNIVERSITY

The Undersigned Faculty Committee Approves the

Thesis of Parag Kothari:

Initial Cell Site Synchronization in LTE System

Fred J. Harris, Chair
Department of Electrical and Computer Engineering

Santosh Nagaraj
Department of Electrical and Computer Engineering

Samuel Kassegne
Department of Mechanical Engineering

19 October 2012
Approval Date
DEDICATION

To my mother, Aruna Kothari, my father, Ramesh Kothari, and Almighty God.
ABSTRACT OF THE THESIS

Initial Cell Site Synchronization in LTE System
by
Parag Kothari
Master of Science in Electrical Engineering
San Diego State University, 2013

Long Term Evolution (LTE) is the latest development in the field of mobile communication system. LTE physical layer uses single carrier modulation scheme SC-OFDM as the uplink (from mobile to base station) due to its relatively low Peak to Average Power Ratio (PAPR) and uses OFDM as downlink (from base station to mobile) due to less complex equalizer. It is important for mobile device to synchronize with the base station in order to transmit or receive data. LTE downlink system uses synchronization signals to detect the frame timing and cell information. LTE uplink system needs time adjustment as mobile devices are at different distances with the base station. To time align the different mobiles, random access procedure is performed. Once uplink and downlink synchronized data transfer is carried between the mobile and base station. The thesis discusses and simulates the signals used during synchronization and random access procedure using MATLAB.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT .................................................................</td>
</tr>
<tr>
<td>LIST OF TABLES .........................................................</td>
</tr>
<tr>
<td>LIST OF FIGURES .........................................................</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS ....................................................</td>
</tr>
<tr>
<td>CHAPTER</td>
</tr>
<tr>
<td>1 INTRODUCTION ..........................................................</td>
</tr>
<tr>
<td>2 LTE (LONG TERM EVOLUTION) .......................................</td>
</tr>
<tr>
<td>3 OFDM (ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING) ....</td>
</tr>
<tr>
<td>3.1 OFDM System Model ................................................</td>
</tr>
<tr>
<td>3.2 PAPR (Peak to Average Power) ..................................</td>
</tr>
<tr>
<td>4 SC-FDM (SINGLE CARRIER FREQUENCY DIVISION MULTIPLEXING)</td>
</tr>
<tr>
<td>5 CELL SEARCH IN LTE ..................................................</td>
</tr>
<tr>
<td>5.1 Initial Cell Search ..................................................</td>
</tr>
<tr>
<td>5.2 Downlink Frame Structure .........................................</td>
</tr>
<tr>
<td>5.3 Zadoff Chu Sequence ...............................................</td>
</tr>
<tr>
<td>5.4 Primary Synchronization Signal ...................................</td>
</tr>
<tr>
<td>5.5 Secondary Synchronization Signal ...............................</td>
</tr>
<tr>
<td>5.6 Broadcast Channel ..................................................</td>
</tr>
<tr>
<td>6 RANDOM ACCESS .......................................................</td>
</tr>
<tr>
<td>6.1 Random Access Procedure ..........................................</td>
</tr>
<tr>
<td>6.2 Preamble Format ......................................................</td>
</tr>
<tr>
<td>6.3 RA Preamble Configuration .........................................</td>
</tr>
<tr>
<td>6.4 RA Preamble Sequence Generation ...............................</td>
</tr>
<tr>
<td>7 SYSTEM DESIGN/MODEL ..............................................</td>
</tr>
<tr>
<td>7.1 Downlink Transmission .............................................</td>
</tr>
<tr>
<td>7.2 PSS Plot ...............................................................</td>
</tr>
<tr>
<td>7.3 SSS Plot ...............................................................</td>
</tr>
</tbody>
</table>
7.4 Uplink Transmission
8 CONCLUSION
REFERENCES
APPENDIX
SAMPLE CODE
LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 5.1. Zadoff-Chu Root Index (u) Corresponding to Physical Layer Identity</td>
<td>22</td>
</tr>
<tr>
<td>Table 6.1. Configuration Index Depending on Preamble Format (0-3)</td>
<td>33</td>
</tr>
<tr>
<td>Table 6.2. Configuration Index for NCS</td>
<td>35</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

Figure 2.1. LTE architecture. ................................................................. 4
Figure 3.1. (A) OFDM transmitter (B) OFDM receiver. ............................ 8
Figure 3.2. Cyclic prefix. ................................................................. 9
Figure 3.3. Sinusoidal output from OFDM subcarriers. .............................. 11
Figure 3.4. Input to a power amplifier. ................................................ 11
Figure 4.1. SC FDM transceivers. ....................................................... 14
Figure 4.2. Comparison of equalizer of OFDMA and SC OFDMA. .......... 15
Figure 5.1. Overview of initial access. .................................................. 17
Figure 5.2. Hierarchy of physical layer cell identity. ................................. 18
Figure 5.3. Downlink frame structure................................................... 19
Figure 5.4. Downlink resource block...................................................... 20
Figure 5.5. Resource mapping of Primary Synchronization Signal ......... 23
Figure 5.6. Resource mapping of Secondary Synchronization Signal ...... 24
Figure 5.7. Generation of Secondary Synchronization Signal ................. 24
Figure 5.8. Mapping of Secondary Synchronization Signal .................. 26
Figure 6.1. Random access procedure. ............................................... 29
Figure 6.2. UE at different distances with eNodeB (base station). .............. 30
Figure 6.3. Near and far user equipment time uncertainty. ....................... 31
Figure 6.4. Preamble format. .......................................................... 32
Figure 7.1. Cell search procedure. ...................................................... 37
Figure 7.2. Autocorrelation of PSS with $u = 25,29,34$. .......................... 38
Figure 7.3. Cross correlation between pair of PSS root index. .................. 39
Figure 7.4. Auto correlation of the secondary synchronization signal .......... 40
Figure 7.5. Match filter output for secondary synchronization signal .......... 40
Figure 7.6. Detected secondary synchronization signal .......................... 41
Figure 7.7. Detect start of signal using auto and cross correlation property. 42
Figure 7.8. Overlap of CP to detect start of the signal ......................... 42
Figure 7.9. Plot for the slot boundary detection ................................................................. 43
Figure 7.10. Match filters for PSS detection ................................................................. 44
Figure 7.11. Detected of PSS ......................................................................................... 44
Figure 7.12. Detected of SSS ......................................................................................... 45
Figure 7.13. Detailed flow diagram for random access procedure ......................... 46
Figure 7.14. Plot for unrestricted cyclic shift with Ncs = 167 ............................... 47
Figure 7.15. Plot for unrestricted cyclic shift with Ncs = 22 ..................................... 48
Figure 7.16. Plot for restricted cyclic shift using Ncs = 18 and u = 631 ..................... 49
ACKNOWLEDGEMENTS

I would like to thank my thesis advisor, Dr. Fred Harris, for his excellent guidance, direction, advice and encouragement throughout my thesis. Sincere thanks to Dr. Santosh Nagaraj and Dr. Sam Kassegne for their valuable time and serving as my thesis committee. I would also like to thank my brother Mayur, sister-in-law Rashmi and my niece Devina for supporting me throughout my thesis work.
CHAPTER 1

INTRODUCTION

Long Term Evolution is the latest advancement in the field of wireless communication system. Wireless communication has travelled a long journey from the first Generation to fourth Generation. Starting in the 1980’s, the first commercial wireless technology that served basic voice communication used analog narrow band FM modulation. The multiple access mechanism of the first generation used Frequency Division Multiple Access (FDMA), having transmission bandwidth in 20 – 30 KHz range. A primary disadvantage of analog systems was their weight and size. Additionally, the narrow band FM systems required significant transmitter energy, which limited their useful on-air time due to battery drain. Second generation phone systems used digital modulation to avoid many of the disadvantages of earlier analog modulation phones. There were two-second generation phone systems, one first developed and fielded in Europe, and one first developed and fielded in the United States. The European system is known as GSM (originally meaning Groupe Spécial Mobile, but later changed to Global System of Mobile), and the United States system is known as CDMA (Code Division Multiple Access). The GSM system employs Gaussian Shaped Minimum Phase Shift Keying (G-MPSK) and time division multiple access (TDMA) with time slot durations of 576.9 µs, occupying 200 kHz of bandwidth. The CDMA system uses Direct Sequence Spread Spectrum (DS-SS) Modulation for its multiple access capabilities and occupies 1.25 MHz bandwidth. Third generation wireless systems were extended versions of the second-generation systems designed primarily to increase wireless data rates. The two phone systems, European and American, started their own projects for third generation mobile phone system called 3rd Generation Partnership Project (3GPP) and 3rd Generation Partnership Project 2 (3GPP2). 3GPP started evolving into the Universal Mobile Telecommunications System (UMTS), an extension to GSM. And 3GPP2 starting working on CDMA2000, evolved from CDMA. Both technologies were based on CDMA. UMTS uses Wideband CDMA (WCDMA) as radio access technology, which uses Direct Sequence CDMA (DS-CDMA) and occupies 5 MHz of bandwidth.
The 3rd Generation Partnership Project (3GPP) was ahead in developing the new radio technology compared to peer systems such as 3GPP2 and IEEE802.16 [1]. The 3GPP standard started from GSM/GPRS, which was based on TDMA and FDMA access technology, then moved towards Code Division Multiple Access, i.e. WCDMA, that used both circuit switched and packet switched technology. Finally, it moved towards mobility and high-speed wireless mobile broadband system Long Term Evolution (LTE), which uses Orthogonal Frequency division Multiplexing (OFDM) access and occupies bandwidth up to 20 MHz [2]. LTE also supports non-3GPP technologies such as WiMAX and CDMA2000.

This thesis provides detailed theory and simulation results of signals used by user equipment for cell search and synchronization with the base station. The outline of the thesis is as follows: Chapter 2 gives a brief overview for the design consideration for LTE system. Chapter 3 provides a description of Orthogonal Frequency Division Multiple (OFDM) access, describing its advantages in multipath scenario. Chapter 3 also discusses the drawbacks of OFDM such as high PAPR. Chapter 4 describes design challenges for the uplink, which is fulfilled by SC-OFDM access. Chapter 5 provides detailed insight into cell search procedure, sequence generations, detection of synchronization signals, and broadcast information. Chapter 6 describes the generation and detection of random access preamble using the Zadoff-Chu sequences. Chapter 7 consists of the simulation parameters and results carried out by using MATLAB.
CHAPTER 2

LTE (LONG TERM EVOLUTION)

Long Term Evolution is the name given to fourth generation mobile system. A description of LTE involves terms such as EPS (Evolved Packet System), EPC (Evolved packet core), and SAE (System Architecture Evolution), which will be introduced and described here. The SAE defines all Internet Protocol (IP) packet switched core-networks. Core network in SAE is EPC. The terms EPC and SAE are used interchangeably. In second and third generation of mobile systems, voice and data use different modes: voice uses circuit switch, and data uses packet switch. In evolved packet core, however, voice and data both use packet switch. LTE, having all IP based packet type core networks, results in simpler and flat architecture, low latency, lower cost, and higher throughput. The LTE architecture is shown in Figure 2.1.

The EPC contains logical nodes used to establish bearing and control with the user equipment.

The main logical nodes in EPC are discussed below:

- Public Data Network gateway (P-GW): The P-GW assigns IP address for each connected UE and provides connectivity to packet data network using access point network. It also provides the quality of service (QoS) depending upon criteria from PCRF.

- Service Gateway (S-GW): S-GW gateway provides path between P-GW and base station for user IP packet transfer, i.e. acts as a router between two. It also collects information including lawful interception.

- Mobile Management Entity (MME): – MME provides signaling and security related messages between E-UTRAN and EPC. It also maintains the information about idle tracking area list of the UE used to transfer and connect incoming session.

The other logical nodes are Home Subscriber Service (HSS), Policy Control, and Charging Rules Function (PCRF) [2]. Advancement in LTE radio access network is called Evolved-UTRAN (E-UTRAN), which only consists of Enhanced-NodeB (eNodeB). eNodeB’s are interconnected with each other. Basic functionality of EUTRAN is radio
Figure 2.1. LTE architecture.

resource management (RRM), header compression, security, and providing connectivity to
the EPC. Combined E-UTRAN (LTE) and SAE (EPC) are known as EPS.

The main driving forces for LTE radio interface and radio access network (RAN)
specification are [3]:

- Increase in data rates, e.g. Downlink (100 Mbps) and Uplink (50 Mbps)
- Reduction in RAN user plane latency to 10ms
- Flexible bandwidth that supports 5, 10, 15, and 20 MHz with backward compatibility
  with to narrow band systems
- Inter-networking with the existing 3GPP and non-3GPP systems
- Reduced delay for connection establishment
- Reasonable decrease in power consumption of User Equipment
- Enhanced MBMS
- Simpler and cost effective system

To achieve and implement given functionality and flexibility, LTE uses advanced technologies that were never used in mobile systems such as OFDM. LTE uses OFDM access in downlink and SC FDM access in uplink.
CHAPTER 3

OFDM (ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING)

3G systems use wideband code division multiple access (WCDMA) in the downlink direction, the cell to mobile link. The multiple access is accomplished by assigning different orthogonal Walsh codes to transmit signals to the user mobile equipment. The Walsh codes are orthogonal in specified intervals in general, but in a multipath environment, the interval is smeared, causing variable delays in the channel of the cellular systems. The loss of well-defined intervals causes the received Walsh codes to lose their mutual orthogonality. Receiver structures were designed to compensate for the effect of the multipath channel. These receivers treat the multipath signals as diversity signals and use multiple de-spreading correlators to resolve and collect the multiple spread spectrum signals propagating along the multiple paths. The multiple matched filters outputs are time and phase aligned and combined as diversity signals in a RAKE receiver. The LTE systems use bandwidths greater than 5MHz, as opposed to the 1.2 MHz used by CDMA signals. The complexity of the RAKE receiver increases dramatically with the increased bandwidth, which motivated the design of an alternate signal set in the LTE system. LTE was designed to support flexible user and channel bandwidths, which was not possible with the WCDMA system. Taking into account the scalability and flexibility of the specification, OFDMA was adopted as downlink access for LTE.

OFDM and OFDMA are variants of Multi-carrier modulation techniques. We will discuss the general structure of multi-carrier modulation, and then return to the OFDM systems.

In today’s world of ever growing demands for increased data rates, a modulation technique that could carry large amounts of information using limited bandwidth became necessary. Multi-Carrier modulation (MCM) is a technique in which a wide available bandwidth is divided into number of smaller bandwidth subcarriers. MCM is designed for
transmitting high data rates with no Inter Symbol Interference (ISI). For a signal to be free of ISI at the detector, the delay spread of the channel should be less than the time duration of the transmitted symbols. If delay spread is larger than symbol duration, then there will be ISI, which will increase the bit error and hence will make detection of the symbol more vulnerable to added channel noise.

In multi-carrier modulation, the problem due to high delay spread of channel can be overcome by dividing the high data rate into number of low data rate streams where the symbol time is much longer than that of the delay spread of the channel. These low data rate streams are modulated to occupy multiple sub-channels to carry the information of the original wide bandwidth data rate stream. In multi-carrier modulation, the data rate transmitted over a sub-channel is significantly lower than the data rate transmitted over single carrier modulation.

The main disadvantage of multi-carrier modulation is the need for a large number of RF transmitters and receivers required to service the multiple narrow-band channels [4]. This would significantly and drastically increase the cost of implementation and the complexity of the system.

In OFDM modulation, the RF transmitters and receivers are implemented by the use of baseband Discrete Fourier Transforms (DFT), which makes the cost and implementation of the system a lot cheaper and easier than that with RF components. Orthogonal frequency division multiplexing is a variant to frequency division multiplexing, where latter uses greater bandwidth than the first. FDM has guard band after each frequency band. But in OFDM, the frequencies bands are designed to overlap but still be mutually orthogonal. Due to the spectral overlap, the modulation process can accommodate more frequencies in the same bandwidth.

### 3.1 OFDM System Model

The basic blocks in an OFDM system (transmitter/receiver) are shown in Figure 3.1.

As shown in the Figure 3.1A, the series to parallel transformation is used to partition the high data rate signal into a number of low data rate signals, keeping the overall data rate of the system constant. The lower data rate signals are then modulated using IFFT, which simplifies the implementation of the system dramatically. IFFT transforms the signal from
frequency domain to time domain. After the IFFT, the modulated time signal is lengthened by appending a cyclic prefix. The cyclic prefix is a segment copied from the back end of the symbol and added in front of the symbol, as shown in Figure 3.2. The cyclic prefix (CP) acts as a guard interval to help mitigate the effects of the ISI and ICI caused by multipath propagation. Symbols experience multipath delays when transmitted in a channel having multiple and variable delays. Adding the CP in the front of the symbol absorbs the transient response related to propagation through the channel and when discarded at the receiver preserves the orthogonality of the signals at the receiver. One of the disadvantages of using
the CP is that it uses a part of bandwidth of the system, which could be used to transmit more data. The CP would not be required in the transmission channel were free of multipath components. Since the CP is used to absorb the channel has delay spread the length of the CP depends on the longest delay spread and the CP length is chosen so that the smearing caused by the longest delay spread is confined to the CP.

At the receiver (see Figure 3.1A), the CP is removed to discard the multipath effect of the channel. The process of discarding the CP interval converts the linear convolution of output data with channel into circular convolution. After removing the cyclic prefix, the signal is passed through a serial to parallel converter. The time domain symbol is then converted to frequency bin independently, using FFT to demodulate the received data. IFFT/FFT pair makes it easy to implement the equalization, especially in frequency domain.

The biggest disadvantage in any multicarrier modulation scheme is high PAPR, i.e. high Peak to Average Power Ratio, which also prevails in OFDM. Apart from this, OFDM is sensitive to frequency offsets and phase noise.

### 3.2 PAPR (Peak to Average Power)

Peak to Average Power Ratio (PAPR) is defined as the ratio of power of a sine wave with amplitude equal to the maximum envelope value (i.e. Peak value of signal) to the power of sine wave with amplitude equal to average of the envelope value. The other term used for it is crest factor, which is equal to the peak amplitude of a waveform divided by its RMS value [5].

This high PAPR requires the Power Amplifier (PA) to be linear within wide dynamic range. Technologies that require high linear power amplifiers are relatively expensive and heavy. Such systems operate with low power efficiency, as efficiency decreases with the
increase in dynamic range. Therefore, it is vital for the communication system based on the OFDM to reduce the PAPR.

Operating the PA in its nonlinear region can distort the signal severely. The nonlinear effects may cause in-band or out-of-band distortion to signals such as spectral spreading, intermodulation, or change in the signal constellation. Out-of-band distortion is particularly troublesome since the transmitted spectrum must satisfy spectral mask constraints. Signal distortion related to PA nonlinearity cannot be inverted by linear signal processing techniques as; equalizers suppress channel distortion. To assure low levels of distortion require to meet spectral mask requirements the PAs require a back off or signal level reduction approximately equal to the PAPR. Operating in back-off mode decreases the efficiency of amplifiers and increases the size and cost of the PA. High PAPR also requires high range and precision for the analog-to-digital converter (ADC) and digital-to-analog converter (DAC); therefore, reducing the PAPR is of practical interest.

We now consider the cause of the high PAPR in an OFDM modem. Considering a 64-point FFT, when single subcarrier is presented to bin k1 of an IFFT, it generates samples of a single complex sin wave with k1 cycles per symbol. When a second subcarrier is presented to k2 of the IFFT, it generates samples of a second complex sin wave with k2 cycles per symbols, and so forth. Similarly, when the 64th subcarrier is presented to bin k64 of the IFFT it generates a complex sinusoid with k64 64 cycles per symbols (see Figure 3.3). The combined summation of these sin waves adds constructively or destructively to form a composite signal, which is presented to the PA. The sum of the multiple sinusoids with random phase and amplitudes will tend to be Gaussian distributed by the central limit theorem. These different carriers may occasionally all line up in phase at some instant and consequently produce a high peak, which is quantified by peak-to-average-power ratio.

As depicted in the Figure 3.4, there is large variation between the peak and average values of the signal. Hence the PA needs to operate in wide linear dynamic range. It can also be inferred from the Figure 3.4 that while the peaks occur rarely, one has to take them into consideration.
Figure 3.3. Sinusoidal output from OFDM subcarriers.

Figure 3.4. Input to a power amplifier.
There are various techniques used to lower the PAPR value of OFDM. These include clipping and filtering, Reservation tones and CCK (Complementary Code Keying), and others. All these techniques add to the complexity and overhead of the system, which is undesirable when we consider it for device such as User Equipment (mobile).

OFDM is used in downlink, as base station does not have any issue with size and the battery power when compared to user equipment. However, to overcome this challenge at uplink, another modulation, the SC-OFDM technique has been selected because it exhibits reduced levels of PAPR compared with OFDM.
CHAPTER 4

SC-FDM (SINGLE CARRIER FREQUENCY DIVISION MULTIPLEXING)

There are different design considerations for uplink (from UE to base station) when compared to downlink (base station to UE). User Equipment or mobile has small size and limited battery power compared with base station. So, in designing the uplink one should consider the fact that the UE should be power efficient and small. Some other important factors that should be taken into consideration are:

- Uplink transmission should be orthogonal
- Able to accommodate various data rates
- Support MIMO techniques
- Able to use frequency diversity
- Exhibit low PAPR

All of the above criteria are satisfied by OFDM except PAPR. As discussed in Chapter 3, OFDM signal has high PAPR, which would increase the cost, size, and weight of the UE, which is undesirable in today’s world [2]. Satisfying all of the above factors, Single Carrier Frequency Division Multiplexing (SC-FDM) access was selected as uplink transmission technique in LTE system.

As in OFDM, the data is first modulated and converted from serial to parallel as shown in Figure 4.1. Then it is passed to an N point FFT to spread the symbols across subcarriers. FFT converts the input symbols to the frequency domain. These N output points from the input FFT are mapped to M input points of an output IFFT (where M is greater than N, depending on number of users). The IFFT transforms the N subcarriers back into complex time domain symbols. After the IFFT, the symbols samples are passed to the parallel to serial converter. To combat multipath propagation, cyclic prefix is added to the data and transmitted sequentially over the RF channel. SC-OFDM does not use single frequency, but it uses single carrier to transmit input spread signal, therefore reducing the PAPR.
At receiver, reverse operations are performed to demodulate the signals. The cyclic prefix is removed to access the ISI signal free. The symbol is de-mapped to M point FFT to covert it from time domain signal to frequency domain signal. After equalizing the symbols in the frequency domain they are de-spread using N point IFFT to convert back into time domain, and at the end - using detector to recover the transmitted data.

SC-OFDM is similar to OFDM, expect DFT pre-coding and spreading at transceiver. As one can see, the basic difference between the OFDM and SC-OFDM is the extra FFT/IFFT pair at transmitter/receiver. An additional FFT block in SC-OFDM spreads the energy of a subcarrier in all the subcarriers, reducing the undesired effect of channel spectral nulls.

At the receiver, SC-OFDM uses the simple to implement frequency domain equalizer of conventional OFDM systems. The OFDM equalization process is performed as scalar corrections applied to each subcarrier. As can be seen from Figure 4.2, before bits can be detected, they must pass through an IFFT to invert the FFT process performed at the transmitter.
Figure 4.2. Comparison of equalizer of OFDMA and SC OFDMA.
CHAPTER 5

CELL SEARCH IN LTE

An OFDM system is sensitive to time and frequency offsets, which requires it to have more precise timing and frequency synchronization for a data to be received. In order to send or receive data, the UE must be synchronized with the network. The synchronization process is achieved through the following steps (see Figure 5.1):

- Initial cell search which includes initial synchronization with the network
- Extract cell system information for cell-specific information
- Access cell system with random access procedure

In this chapter, the main discussion will be about initial cell search, synchronization and how to extract cell specific information.

5.1 INITIAL CELL SEARCH

When User Equipment (UE) is powered ON in cellular mobile system, it must perform cell search and synchronization with the base station prior to sending or receiving data. It is very important to perform time and frequency synchronization procedure to correctly determine the start of the signal and select best possible base station for a given UE. This procedure is known as initial cell search. It is also performed while supporting the mobility of the UE to continuously search for RSSI (Received Signal Strength Indicator) from the neighboring cells during handover or when terminal is in idle mode.

Cell search includes the following steps:

- Synchronization (time and frequency with base station)
- Frame arrival on the downlink channel, for UE to start decoding cell information accurately
- Identify correct PCI (Physical layer Cell Identity)

The main signals used in cell search synchronization process are synchronization signals broadcast by the LTE cell, i.e. from base station to mobile, Primary Synchronization Signal (PSS), and Secondary Synchronization Signal (SSS). These signals provide information about physical layer ID, frame slot boundaries, frequency synchronization, group
cell ID, and radio frame timing. With all the given information, time-frequency synchronization and physical layer cell id (PCI) can be extracted. In LTE systems, there are total of 504 different PCI. These cell identities can be derived using a hierarchal scheme which consists of 168 different physical layer cell identity groups numbering from 0 to 167, and each group consists of 3 physical layer identities from 0 to 2. The physical layer cell identity hierarchy is shown in Figure 5.2.

In addition to synchronization signals, physical broadcast channel (PBCH) is decoded for initial cell search. PBCH carries system information such as system bandwidth and system frame number (SFN) in Master Information Block (MIB).

Figure 5.1. Overview of initial access.
5.2 DOWNLINK FRAME STRUCTURE

Let us now discuss the radio frame structure used in LTE. The LTE radio frame is 10ms long, having 10 sub frames of 1ms long each. Each sub frame is subdivided into 2 slots of 0.5ms. Further, each slot has either 6 or 7 OFDM symbols depending on the length of cyclic prefix. If extended cyclic prefix is used, 6 OFDM symbols are used in 0.5ms slot, while if normal cyclic prefix is used, 7 OFDM symbols are used in 0.5ms slot. Please refer to Figure 5.3 [6] and 5.4 [6].

In FDD (Frequency Division Duplexing) LTE, the PSS and SSS are found in first and sixth sub-frames, or one can call that zero and tenth slot of 10ms frame of LTE downlink. PSS and SSS signals occur twice in a 10ms frame. PSS is transmitted in last OFDM symbol of the zero and tenth slot; both are identical to each other. With PSS detection, sub frame synchronization timing and Physical Layer Identity (0-2) is achieved. SSS is transmitted in the symbol prior to PSS. SSS also occur twice in 1ms frame but are different in each slot. The purpose for different SSS is to differentiate between the first and second half of the radio
frame for frame synchronization [2]. With detection of SSS, physical cell identity group (0 - 167) is determined.

Each of PSS and SSS are of 62 length sequence symbols. PSS and SSS are mapped to the center 62 subcarriers around zero frequency (or d.c. zero frequency index) subcarrier. The d.c. subcarrier is left unused to avoid d.c. injection during direct conversion at the receiver. The PSS and SSS are transmitted over central 72 subcarriers (six resource block) around d.c. subcarrier, the remaining five subcarriers on each side are zero padded (unused). Of the 72 subcarriers 62 subcarriers are used for transmission, and the 10 remaining subcarriers are zero padded. These 72 subcarriers occupy 1.08 MHz bandwidth, as shown in Figure 5.4 [6]. The UE scans the minimum bandwidth of the available frequencies to extract the basic information of the LTE cell such as system frame number, physical channel cell identity, multiple access used (FDD/TDD), normal or extended cyclic prefix used, and transmission bandwidth. PSS uses special modulation sequence known as the Zadoff-Chu sequence for its generation. In the next section, the Zadoff-Chu sequence will be introduced and described.
5.3 ZADOFF CHU SEQUENCE

The Zadoff-Chu sequence is widely used in the LTE system. The Zadoff-Chu sequence is also called as CAZAC sequence [7], an acronym derived from its desirable property of Constant Amplitude, Zero AutoCorrelation. The sequence is formed as a quadratic phase modulated sinusoid, which is responsible for the constant time domain envelope. The constant envelope also imparts a low PAPR (Peak to Average Power Ratio) to the time sequence, which is a desirable property for any sequence. The low PAPR [1] permits the transmitter power amplifiers to operate in its high efficiency regime. The quadratic phase of the sinusoid is responsible for desirable property that its circular auto correlation has a single correlation peak and zero side lobes, hence the name zero auto correlation. With the auto correlation function being an impulse, we can infer that its spectrum is a constant, a very desirable property for frequency domain channel estimation [7]. The Zadoff-Chu sequence is a complex sinusoid with quadratic phase [8] given by:

\[
x_u(m) = \begin{cases} 
  e^{-j\frac{mum^2}{N_{ZC}}} & \text{when } N_{ZC} \text{ is even} \\
  e^{-j\frac{mum(m+1)}{N_{ZC}}} & \text{when } N_{ZC} \text{ is odd} 
\end{cases}
\]

(5.1)

Where \(N_{ZC}\) is length of the Zadoff-Chu sequence, and \(u\) one of 3 selected integers called the root index.

The following properties are exhibited by set of the Zadoff-Chu (CAZAC) Sequences,

- Each sequence should have constant amplitude
- Zero Autocorrelation, i.e. it has ideal autocorrelation. Circular convolution of sequence with itself gives delta function at zero lag.
- Cyclic cross correlation of pair of sequence is low and constant amplitude

One important property of the ZC sequence is that it does not need DFT operation as it is in frequency domain already. Interestingly, the DFT of a ZC sequence is another ZC sequence.

5.4 PRIMARY SYNCHRONIZATION SIGNAL

Primary Synchronization Signal in LTE downlink frame appears twice, first in slot 0 and the then in slot 10. Both the slots carry the same sequence. PSS provides information about physical layer identity, which can have 3 different values (0-2) depending [9] upon the
root index of the Zadoff-Chu sequence (see Table 5.1). Once UE decodes PSS, it gets information about 5ms frame timing (sub frame timing) [2].

| Table 5.1. Zadoff-Chu Root Index \(u\) Corresponding to Physical Layer Identity |
|------------------|--------------------------|
| \(N_{id}^2\)     | Root Index (u)           |
| 0                | 25                       |
| 1                | 29                       |
| 2                | 34                       |

PSS is transmitted over six resource blocks but uses only 62 subcarriers around d.c zero frequency index subcarrier, with the remaining 5 subcarriers on each side zero padded, as depicted in Figure 5.5. From now on, we will denote the physical cell identity as \(N_{id}\), physical layer identity (PSS) as \(N_{id}^{(2)}\), and physical cell identity group (SSS) as \(N_{id}^{(1)}\). PSS is generated using Equation 5.2 [8]:

\[
d_u(n) = \begin{cases} 
  e^{-j\frac{\pi}{63}n^u}, & n = 0,1,...,30 \\
  e^{-j\frac{\pi}{63}(n+1)(n+u)}, & n = 31,32,...,61 
\end{cases} \tag{5.2}
\]

Where the ZC root sequence index \(u\) is 25, 29 and 34 for \(N_{id}^{(2)} = 0,1,2\) respectively.

The Zadoff-Chu sequence of length 62 is centered around the d.c. zero frequency index subcarrier to avoid d.c. injection. The roots used to generation the PSS with physical layer identity \(N_{id}^2 = 0, 1, 2\) are \(u = 25, 29, 34\) respectively. These sets of roots are selected due to good autocorrelation and cross correlation properties, resulting in better frequency and time offset sensitivity. PSS can detect up to +/- 7.5 KHz of frequency offset due to the frequency domain autocorrelation and low frequency offset sensitivity [2]. The UE uses non-coherent detection, as it detects PSS without prior knowledge of channel.

### 5.5 Secondary Synchronization Signal

Secondary synchronization signal helps to detect radio frame timing and PCI group. SSS uses interleaved maximal length sequence (m-sequence of length 31) to form a sequence of length 62. The SSS sequence of length 62 is mapped to resource block in the same manner as PSS, i.e. transmitting the frequency domain signal around the d.c. zero frequency index.
subcarrier. SSS also uses six resource blocks, with zero padding on remaining subcarriers on each side, as shown in the Figure 5.6.

The sequence of length 62 SSS is generated using two 31-length BPSK sequences of modulated signals, which are generated using the two different cyclic shifts of the same m-sequence of length 31. The two generated codes are interchanged with the transmission of first and second SSS in 10ms radio frame [2]. Once two 31 BPSK sequences are generated, they are scrambled and interleaved to make a 62 length sequence. The two different SSS enable UE to detect 10 ms radio frame timing. The concatenated sequence is scrambled with code depending on PSS. The sequence generation is shown in Figure 5.7. The SSS sequence also exhibits good frequency domain properties. SSS can also be detected with frequency offset up to +/- 7.5 kHz [2]. When UE starts decoding SSS, it has knowledge about the channel as PSS is already known. SSS detection is coherent in nature, as the channel information is known.
Figure 5.6. Resource mapping of Secondary Synchronization Signal.

Figure 5.7. Generation of Secondary Synchronization Signal.

Here is the detailed explanation of SSS generation. The combination of two 31-length sequences generating SSS is altered in 0th and 10th slot. So, let us explain 0th slot SSS generations first.

- Generate a basic 31 length sequence using LFSR:

\[ s(i) = 1 - 2x(i), \quad 0 \leq i \leq 30, \quad x(i) \text{ defined by} \]
\[ x(i + 5) = (x(i + 2) + x(i)) \mod 2, \quad 0 \leq i \leq 25 \]
With initial conditions defined as:
\[ x(0) = 0, \quad x(1) = 0, \quad x(2) = 0, \quad x(3) = 0, \quad x(4) = 1 \]
This generates a 31 length sequence with given initial condition. The above equation is used to convert the binary sequence into BPSK sequence.

- Using cyclic shift property, two sequences are generated. To get the indices for the cyclic shift, the following equations are used:

  \[ m_0 = m' \mod 31 \]
  \[ m_1 = (m_0 + \lfloor m'/31 \rfloor + 1) \mod 31 \]
  \[ m' = N^{(1)}_{\text{id}} + q(q + 1)/2, \quad q = \left\lfloor \frac{N^{(1)}_{\text{id}} + q'(q' + 1)/2}{30} \right\rfloor, \quad q' = \left\lfloor \frac{N^{(1)}_{\text{id}}}{30} \right\rfloor \]

According to the equation, cyclic shift indices depend on physical cell identity group \(N_{\text{id}}^{(1)}\)

- The two 31 length sequences now can be generated with cyclic indices of \(m_0\) and \(m_1\) as follows:

  \[ s^{(m_0)}_0(n) = \bar{s}((n + m_0) \mod 31) \]
  \[ s^{(m_1)}_1(n) = \bar{s}((n + m_1) \mod 31) \]

- By now, we have two 31-length BPSK modulated sequences. These sequences are then scrambled, using different cyclic shifts of scrambling code depending on PSS. The basic scrambling code is generated using

  \[ \bar{c}(i) = 1 - 2x(i), \quad 0 \leq i \leq 30, \quad x(i) \text{ defined by} \]
  \[ x(i + 5) = (x(i + 3) + x(i)) \mod 2, \quad 0 \leq i \leq 25 \]

With initial conditions, shown as
\[ x(0) = 0, \quad x(1) = 0, \quad x(2) = 0, \quad x(3) = 0, \quad x(4) = 1 \]
After generating the basic, the 2 scrambling codes can be generated using cyclic shift property

  \[ c_0(n) = \bar{c}((n + N^{(2)}_{\text{id}}) \mod 31) \]
  \[ c_1(n) = \bar{c}((n + N^{(2)}_{\text{id}} + 3) \mod 31) \]

- As both sequences are interleaved to generate a 62 length sequence, one sequence is sent over the even subcarrier, and the other over the odd subcarrier, as shown in Figure 5.8.

- Odd sequence is again scrambled with the sequence containing indices of even \(m_0\). This scrambling code also uses LFSR for its generation, as previous scrambling code.

  \[ z^{(m_0)}_1(n) = \bar{z}((n + (m_0 \mod 8)) \mod 31) \]
Final sequence is than can be expressed as:

\[ d(2n) = s_0^{(m_0)}(n)c_0(n) \text{ in subframe 0} \]
\[ d(2n + 1) = s_1^{(m_1)}(n)c_1(n)e_1^{(m_0)}(n) \text{ in subframe 0} \]

Similarly, for slot 10 Secondary Synchronization Signal, the indices \( m_0 \) and \( m_1 \) are interchanged for generation of 62 length sequence

\[ d(2n) = s_1^{(m_0)}(n)c_0(n) \text{ in subframe 5} \]
\[ d(2n + 1) = s_0^{(m_0)}(n)c_1(n)e_1^{(m_1)}(n) \text{ in subframe 5} \]

5.6 **Broadcast Channel**

The Broadcast channel (BCH) in any cellular system is used to broadcast the cell system information to the cell site that allows other channels to be configured and operated. Therefore, it is important to decode the Physical BCH to get hands on system information. PBCH carries the information of Master Information Block (MIB). MIB contains limited but important information needed for initial cell access for UE. Information carried out by MIB provides cell bandwidth in terms of resource block, Physical Hybrid ARQ Indicator Channel (PHICH), and system frame number, which are continuously broadcasted to the cell. The PBCH is designed in such a way that:
• It does not need system bandwidth to decode the broadcasted information
• Has low latency time and power is consumed by UE
• Can be decoded reliably at the edge of cell site
• System overhead should be low

The PBCH can be decoded while the system actual bandwidth is unknown, as it is centered on the DC subcarrier as in PSS and SSS. PBCH uses 72 subcarriers, so it can be decoded even when search is performed at minimum bandwidth of system. The center frequency is previously known from PSS and SSS.

The broadcasting PBCH channel, uses 4 sub frames spread over time interval of 40 ms with one subframe in each 10ms frame.

System overhead is kept low by providing the minimum information needed for the initial access of cell. Master information Block is sent over PBCH. MIB is 14 bits long sent over span of 40ms [2].

The reliable detection can be achieved by using time diversity, FEC, and antenna diversity. The PBCH is transmitted over a span of 40ms, so if a portion of signal is lost due to fading, one has other parts to decode the rest of the PBCH.

Each of the 4 subframes is self-decodable if the channel condition is good for the estimation, so one does not have to wait for full 40ms to decode the broadcast channel.
CHAPTER 6

RANDOM ACCESS

For User Equipment (UE) to start scheduling for uplink transmission it must be time synchronized with the base station [2]. Random access is performed when a UE is switched ON (initial access), moved from idle mode to connected mode, or during handoff or radio link failures (RLF). When random access is initiated, it is always assumed that UE is already time synchronized in downlink with eNodeB. As the downlink synchronization is done via Primary synchronization signal, Secondary Synchronization Signal, and Broadcast Channel, which provides information about the cell ID, cell bandwidth, and other random access parameter information. Once the UE is downlink synchronized, the random access preamble must be transmitted from UE to estimate and adjust the uplink transmission timing [8]. Once eNodeB receives the random access preamble transmitted by UE, giving the estimate of timing offset, it sends the random access response (RAR) back to UE. RAR contains information for time advancement, uplink resource information, and preamble ID. If the preamble ID matches at UE, the random access attempt is successful. UE then uses the time advance information and adjusts the uplink transmission time offset (see Figure 6.1). UE now can start requesting resource or SR (schedule request) [8].

6.1 RANDOM ACCESS PROCEDURE

RA procedure can occur in two ways, contention-based and non-contention (contention-free) based. In contention-based random access, UE randomly selects a preamble for transmission. There might be a possibility that more than one UE select the same preamble at the same time. Hence a contention-based resolution is needed. Contention-based procedure is used during initial access. Contention-free access is used during time-critical cases. In contention-free access, UE is provided with a unique preamble sequence, so no extra time is needed to resolve it. It is used during handover or downlink data.
In LTE system, random access uses 6 bits to transmit the preamble, which makes a total of $2^6 = 64$ preamble sequences per cell. These 64-preamble sequences are divided between contention-free access (handover) and contention-based procedure (initial access).

The contention-based preamble group is further divided into 2 subgroups depending on size of uplink transmit data. The eNodeB broadcasts the information of preambles, stating group and its significance [2]. If a UE uniquely selects a random preamble from one of the two subgroups of contention-based procedure, it is likely eNodeB decodes the transmitted preamble from UE. The eNodeB decides the number of preambles in each subgroup depending on the type of load in cell. Initial preamble transmission power is based on open loop estimation. UE transmits the preamble with such a power that it is detected by eNodeB. Random access message is sent over physical Random Access Channel called Physical Random Access Channel (PRACH).

After the RA preamble is received by eNodeB in second step, an RA response is sent over Downlink Shared Channel (DL-SCH) i.e. Physical Downlink Shared Channel (PDSCH), which includes information such as Preamble ID, time alignment information, uplink scheduled grant resource, and a temporary ID RA-RNTI (Random access radio network temporary identity). UE expects the RA response within a certain time window after PRACH is transmitted; if it does not receive or was not able to decode RAR, the PRACH signal has to be retransmitted after a certain time [8]. eNodeB controls the power at which
the RAR message is transmitted. Power of the message transmitted is incremented with every failure.

After successful decoding of RAR, UE is time-aligned with the eNodeB.

6.2 PREAMBLE FORMAT

The random access preambles are transmitted at most once in a sub frame. They are not spread across frequency, but they are spread across time domain to reduce the average waiting time before RA can be re-initialized [1].

As of now, one is synchronized in downlink via PSS, SSS, BCH, and system information. Uplink is not synchronized until random access procedure is successfully performed. All the UE’s are at different distances w.r.t the eNodeB (see Figure 6.2). This makes difficult for the base station to decode the information sent by users from different locations at the same time as it creates the uncertainty for frame arrival time at base station. In order to time-align the message frames sent by different mobile users, random access procedure is performed. In large cells, UE at cell edge will have longer delay then UE near eNodeB (see Figure 6.3). There is a timing difference between the two UE’s, hence a guard time is introduced to track the difference and avoid collision in transmission.

The value of guard time depends on the cell size. As cell size increases, the round trip propagation increases, which is given by 6.7µs/km. Hence for a cell size of 100km a guard
time of 670µs is used [2]. In addition to the preamble sequence and guard time, cyclic prefix is used for simpler and better processing at eNodeB because of its frequency domain processing. This CP (cyclic prefix) and GT (guard time) act as an overhead for the cells which are small but using the same GT and CP as the large size cell, so depending on the cell size we use different types of preamble formats. Typically in FDD there are 4 preamble formats from 0 to 3 (Figure 6.4). The smallest cell size format is of 15Km, using 0.1ms as CP and 0.1ms as guard time. The random access preamble is 0.8ms long. For larger cell size, formats 1-3 are used. In formats 2 and 3, repeating the preamble twice increases the RA preamble detection possibility.

### 6.3 RA PREAMBLE CONFIGURATION

MAC layer initiates random access preamble. There are 16 configurations for each preamble format (0–3) for resource allocation. There is at most one RA resource per sub frame. If more than one RA resource needs to be sent, it will be sent in time multiplex rather than frequency multiplex, as eNodeB needs to give quick response, so it does not transfer RA response after the time window [2].

RA does not transmit any real user data; it is used for signaling purposes only. The overheads of random access can be calculated as follows. Consider a system bandwidth of 50 resource blocks and configuration 6 (see Table 6.1) with RA allowed in all the system frame numbers. The overhead is given by ((6/50) *(2/10)) =2.4%, as configuration 6 uses 2 sub frames in a frame for random access transmission. This gives a rough idea of how much
overhead is caused by random access. Overhead depends on the cell bandwidth and the load onto the eNodeB. If the system bandwidth is small, lower number of RA attempts is needed. Configuration 3 might be useful for smaller cells with less number of users.

6.4 RA PREAMBLE SEQUENCE GENERATION

Random Access preambles are generated using the Zadoff-Chu sequences. Zadoff-Chu sequences are also used in generation for synchronization signal. The sequence length of a random access preamble is 839. In order to maximize number of available sequences, a prime length Zadoff-Chu sequence is selected. RA preamble uses center bandwidth of 1.08 MHz with subcarrier spacing of 1.25 KHz, corresponding length turns out to be 864 subcarriers. In order to maximize the available number of sequences with optimum cross correlation, a prime numbered sequence is selected, but 864 is not prime. Available sequence length can be around 864, i.e. less than 864 because if it is more than 864, there will be inference in data subcarrier. The sequence length must be selected from 829, 839, 853, 857, 859, 863 and 877. PRACH uses guard band to keep minimum interference from the adjust channels. Therefore, 25 subcarriers are assigned as a guard band that would be in 12.5 in each side of PRACH preamble, keeping the preamble length to 839, which seems to be best suited. Zadoff-Chu sequence of length 839 also satisfies property of having good cross
<table>
<thead>
<tr>
<th>PRACH Configuration Index</th>
<th>Preamble Format</th>
<th>System frame number</th>
<th>Subframe number</th>
<th>PRACH Configuration Index</th>
<th>Preamble Format</th>
<th>System frame number</th>
<th>Subframe number</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>Even</td>
<td>1</td>
<td>32</td>
<td>2</td>
<td>Even</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>Even</td>
<td>4</td>
<td>33</td>
<td>2</td>
<td>Even</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>Even</td>
<td>7</td>
<td>34</td>
<td>2</td>
<td>Even</td>
<td>7</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>Any</td>
<td>1</td>
<td>35</td>
<td>2</td>
<td>Any</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>Any</td>
<td>4</td>
<td>36</td>
<td>2</td>
<td>Any</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>Any</td>
<td>7</td>
<td>37</td>
<td>2</td>
<td>Any</td>
<td>7</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>Any</td>
<td>1, 6</td>
<td>38</td>
<td>2</td>
<td>Any</td>
<td>1, 6</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>Any</td>
<td>2, 7</td>
<td>39</td>
<td>2</td>
<td>Any</td>
<td>2, 7</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>Any</td>
<td>3, 8</td>
<td>40</td>
<td>2</td>
<td>Any</td>
<td>3, 8</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>Any</td>
<td>1, 4, 7</td>
<td>41</td>
<td>2</td>
<td>Any</td>
<td>1, 4, 7</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>Any</td>
<td>2, 5, 8</td>
<td>42</td>
<td>2</td>
<td>Any</td>
<td>2, 5, 8</td>
</tr>
<tr>
<td>11</td>
<td>0</td>
<td>Any</td>
<td>3, 6, 9</td>
<td>43</td>
<td>2</td>
<td>Any</td>
<td>3, 6, 9</td>
</tr>
<tr>
<td>12</td>
<td>0</td>
<td>Any</td>
<td>0, 2, 4, 6, 8</td>
<td>44</td>
<td>2</td>
<td>Any</td>
<td>0, 2, 4, 6, 8</td>
</tr>
<tr>
<td>13</td>
<td>0</td>
<td>Any</td>
<td>1, 3, 5, 7, 9</td>
<td>45</td>
<td>2</td>
<td>Any</td>
<td>1, 3, 5, 7, 9</td>
</tr>
<tr>
<td>14</td>
<td>0</td>
<td>Any</td>
<td>0, 1, 2, 3, 4, 5, 6, 7, 8, 9</td>
<td>46</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>15</td>
<td>0</td>
<td>Even</td>
<td>9</td>
<td>47</td>
<td>2</td>
<td>Even</td>
<td>9</td>
</tr>
<tr>
<td>16</td>
<td>1</td>
<td>Even</td>
<td>1</td>
<td>48</td>
<td>3</td>
<td>Even</td>
<td>1</td>
</tr>
<tr>
<td>17</td>
<td>1</td>
<td>Even</td>
<td>4</td>
<td>49</td>
<td>3</td>
<td>Even</td>
<td>4</td>
</tr>
<tr>
<td>18</td>
<td>1</td>
<td>Even</td>
<td>7</td>
<td>50</td>
<td>3</td>
<td>Even</td>
<td>7</td>
</tr>
<tr>
<td>19</td>
<td>1</td>
<td>Any</td>
<td>1</td>
<td>51</td>
<td>3</td>
<td>Any</td>
<td>1</td>
</tr>
<tr>
<td>20</td>
<td>1</td>
<td>Any</td>
<td>4</td>
<td>52</td>
<td>3</td>
<td>Any</td>
<td>4</td>
</tr>
<tr>
<td>21</td>
<td>1</td>
<td>Any</td>
<td>7</td>
<td>53</td>
<td>3</td>
<td>Any</td>
<td>7</td>
</tr>
<tr>
<td>22</td>
<td>1</td>
<td>Any</td>
<td>1, 6</td>
<td>54</td>
<td>3</td>
<td>Any</td>
<td>1, 6</td>
</tr>
<tr>
<td>23</td>
<td>1</td>
<td>Any</td>
<td>2, 7</td>
<td>55</td>
<td>3</td>
<td>Any</td>
<td>2, 7</td>
</tr>
<tr>
<td>24</td>
<td>1</td>
<td>Any</td>
<td>3, 8</td>
<td>56</td>
<td>3</td>
<td>Any</td>
<td>3, 8</td>
</tr>
<tr>
<td>25</td>
<td>1</td>
<td>Any</td>
<td>1, 4, 7</td>
<td>57</td>
<td>3</td>
<td>Any</td>
<td>1, 4, 7</td>
</tr>
<tr>
<td>26</td>
<td>1</td>
<td>Any</td>
<td>2, 5, 8</td>
<td>58</td>
<td>3</td>
<td>Any</td>
<td>2, 5, 8</td>
</tr>
<tr>
<td>27</td>
<td>1</td>
<td>Any</td>
<td>3, 6, 9</td>
<td>59</td>
<td>3</td>
<td>Any</td>
<td>3, 6, 9</td>
</tr>
<tr>
<td>28</td>
<td>1</td>
<td>Any</td>
<td>0, 2, 4, 6, 8</td>
<td>60</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>29</td>
<td>1</td>
<td>Any</td>
<td>1, 3, 5, 7, 9</td>
<td>61</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>30</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>62</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>31</td>
<td>1</td>
<td>Even</td>
<td>9</td>
<td>63</td>
<td>3</td>
<td>Even</td>
<td>9</td>
</tr>
</tbody>
</table>
correlation between maximum available Zadoff-Chu sequences and having less interference from adjust channels.

Thus the preamble uses basic Zadoff-Chu sequence shown in Equation 6.1:

\[ x_v(n) = e^{-j\frac{\pi n N_{\text{ZC}}}{N_{\text{ZC}}}}, \quad 0 \leq n \leq N_{\text{ZC}} - 1 \]  

(6.1)

where \( N_{\text{ZC}} \) is length of ZC sequence equal to 839

The RA preamble uses the cyclic shift property of ZC sequence to generate the sequence. The cyclic shift sequences generated from a single Zadoff-Chu sequence are favored over different Zadoff-Chu sequences. Sequences generated from different Zadoff-Chu sequence are not orthogonal. Zadoff-Chu cyclic shifts (CS) have several properties that make it the strongest sequence for uplink transmission, such as good autocorrelation property for timing estimate at base station, low PAPR value, and good cross correlation property. Inter-cell interference is minimum when the sequences are the same ZC root sequence. These cyclic shifted ZC sequences are generated using Equation 6.2 [6]:

\[ x_{v,n} = x_n((n + C_v) \mod N_{\text{ZC}}) \]  

(6.2)

Where \( C_v \) is cyclic shift and is given by:

\[ C_v = \begin{cases} 
\frac{vN_{\text{CS}}}{N_{\text{ZC}}}, & v = 0, 1, ..., \left\lfloor \frac{N_{\text{ZC}}}{N_{\text{CS}}} \right\rfloor - 1, N_{\text{CS}} \neq 0 \text{ for unrestricted sets} \\
0, & N_{\text{CS}} = 0 \text{ for unrestricted sets} \\
\lfloor v/(n_{\text{RA}}) \rfloor + (v \mod n_{\text{RA}})N_{\text{CS}}, & v = 0, 1, ..., n_{\text{RA}}N_{\text{group}} - 1, \frac{n_{\text{RA}}}{n_{\text{group}}} - 1 \text{ for restricted sets} 
\end{cases} \]  

(6.3)

There are two types of cyclic shifts sets in LTE system: restricted and unrestricted sets. First, we will discuss the unrestricted cyclic shift. There are 16 cyclic shift configurations (see Table 6.2) used for generation of 64 preamble sequences in a cell. The cyclic shift offset \( N_{\text{CS}} \) is selected such as to keep ZCZ for the sequences to maintain the orthogonality even if the timing is unknown or if there is delay spread. Hence, the cyclic shift offset is selected as the minimum integer that accumulates the cell’s maximum delay spread, time uncertainty of the UE, and the guard time. Therefore, larger cells require larger cyclic shift offset to keep the orthogonality of the sequences. Larger cyclic shift value used for larger cell provides large delay spread, it reduces the number of available cyclic shifts. Hence, we need more than one root sequence to generate all the 64 preambles.
Table 6.2. Configuration Index for NCS

<table>
<thead>
<tr>
<th>zeroCorrelationZoneConfig</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>NCS Value</td>
<td>0</td>
<td>13</td>
<td>15</td>
<td>18</td>
<td>22</td>
<td>26</td>
<td>32</td>
<td>38</td>
<td>46</td>
<td>59</td>
<td>76</td>
<td>93</td>
<td>119</td>
<td>167</td>
<td>279</td>
<td>419</td>
</tr>
<tr>
<td>Value</td>
<td>15</td>
<td>18</td>
<td>22</td>
<td>26</td>
<td>32</td>
<td>38</td>
<td>46</td>
<td>55</td>
<td>68</td>
<td>82</td>
<td>100</td>
<td>128</td>
<td>158</td>
<td>202</td>
<td>237</td>
<td></td>
</tr>
</tbody>
</table>


Hence the number of available cyclic shifts depends on the cyclic shift value in the unrestricted cyclic shift case.

The unrestricted cyclic shifts are used when there is no or very low Doppler effect. With introduction of high Doppler effect, the zero correlation zone property of ZC sequence does not stand, i.e. the orthogonality of the sequences is not maintained. The high Doppler effect induces the frequency offset to the incoming sequences, which affects the detection performance and creates false alarm. The problem for high Doppler shift is taken care of in LTE by restricting the number of available cyclic shifts. This approach decreases the number of available cyclic shifts for a given the Zadoff-Chu sequence and increases the complexity of the system.
CHAPTER 7

SYSTEM DESIGN/MODEL

The chapter discusses the implementation and simulation of cell search and random access using MATLAB.

7.1 DOWNLINK TRANSMISSION

The process of the downlink synchronization can be summarized into the flow diagram shown in Figure 7.1.

7.2 PSS PLOT

The parameters used for PSS sequence generation:

- The subcarrier spacing is $\Delta f = 15 \text{ KHz}$
- Transmitted bandwidth = 1.08 MHz
- Number of available subcarrier = 72
- Utilized subcarrier = 62 (centered around d.c. zero frequency index subcarrier)
- Guard subcarrier = 5 (either sides of PSS)
- Length of PSS sequence = 62

PSS is transmitted from eNodeB (base station) to UE. Downlink uses OFDM modulation technique, as the received signal is demodulated affectively using frequency-based equalizer at UE. As we know that $N^{\text{cell}}_{\text{ID}} = 3N^{(1)}_{\text{ID}} + N^{(2)}_{\text{ID}}$

$$N^{(1)}_{\text{ID}} = 0...168$$  \hspace{1cm} (7.1)

$$N^{(2)}_{\text{ID}} = 0, 1, 2$$  \hspace{1cm} (7.2)

And the value of physical layer ID $N^{(2)}_{\text{ID}}$ corresponds to root index of the ZC sequence = 25, 29, 34.

The Figure 7.2 indicates the autocorrelation of individual root index sequence with itself and is normalized.
Figure 7.1. Cell search procedure.
The cross correlation property between pairs of the Zadoff-Chu sequences in LTE system can be seen in Figure 7.3. Refer to the Appendix for MATLAB implementation of the PSS.

From Figure 7.3, the cross correlation property is good for pair 25, 29 and 29, 34 but is not so good for pair 34, 25.

### 7.3 SSS PLOT

The parameters used for SSS sequence generation:

- The subcarrier spacing is $\Delta f = 15$ KHz
- Transmitted bandwidth = 1.08 MHz
- Number of available subcarrier = 72
- Utilized subcarrier = 62 (centered around d.c. zero frequency index subcarrier)
- Guard subcarrier = 5 (either sides of SSS)
- Length of SSS = 62

$$N_{id}^{(1)} = 0...168$$  \hspace{1cm} (7.3)
Figure 7.3. Cross correlation between pair of PSS root index.

Figure 7.4 is shows Auto correlation of randomly generated SSS for 6 different $N_{id}^{(1)} = 76, 128, 53, 131, 78, 5$. Where $N_{id}^{(1)} = 76$ is normalized.

An example of transmitting a SSS $N_{id}^{(1)} = 5$ and receive it at the receiver via match filter is shown in Figure 7.5. For simulation purpose 6 match filters were used, but in practical they are more in numbers depending on implementation.

It becomes clearer when all of outputs of match filter are put onto one plot Figure 7.6. The SSS $N_{id}^{(1)} = 5$ is detected correctly at the match filter with highest correlation peak.

Now we have transmitted the PSS, SSS, and BCH information on to OFDM modulated symbols in a 10ms frame. The PSS is transmitted at 0th and 10th slot on 7th OFDM symbol. SSS is sent in previous OFDM symbol as PSS. BCH is transmitted after the PSS in 4 consecutive OFDM symbols.
Figure 7.4. Auto correlation of the secondary synchronization signal.

Figure 7.5. Match filter output for secondary synchronization signal.
The subcarrier spacing is $\Delta f = 15$ KHz

- Transmitted bandwidth = 1.08 MHz
- Number of available subcarrier = 72
- Utilized subcarrier = 62 (centered around d.c. zero frequency index subcarrier)
- Guard subcarrier = 5 (either sides signals)
- Length of PSS = 62
- Length of SSS = 62

$N_{ID}^{(1)} = 0...168$ \hspace{1cm} (7.4)

$N_{ID}^{(2)} = 0, 1, 2$ \hspace{1cm} (7.5)

Size of FFT = 128 \hspace{1cm} (7.6)

NCP = 32 \hspace{1cm} (7.7)

Once the 10ms frame is transmitted from base station. The UE receiver is always searching for the start of the signal. This is done using the property of cyclic prefix and sliding window technique. In this technique the incoming signal is delayed by 128 (length of
FFT) samples. The start of the signal can be found by ratio of the average ((length of cyclic prefix)) of cross correlation between incoming and delayed version of signal, and the average (length of cyclic prefix) of autocorrelation of delayed version of signal with itself. This ratio gives out the high correlation value from which the start of the signal can be detected and the receiver must start processing the arriving signal [10] (see Figure 7.7 and 7.8).

![Figure 7.7. Detect start of signal using auto and cross correlation property.](image)

From plot in Figure 7.9, information about type of cyclic prefix, length of CP, and the start of the signal can be extracted.

![Figure 7.8. Overlap of CP to detect start of the signal.](image)
For PSS detection, receiver should have three match filters corresponding to each root index. The incoming signal is passed through the match filters to detect the PSS (Figure 7.10). Thus, the PSS signal is detected.

From the Figure 7.11, the detected PSS is of root index 29, as largest correlation spike is measured for $u = 29$, which corresponds to $N_{ID}^{(2)} = 1$. Now, one has knowledge of $N_{ID}^{(2)}$ and sub frame timing [9]. After the successful detection of PSS, the detection of SSS is also done via match filters. In the simulation, 6 match filters are used for 6 different $N_{ID}^{(1)}$. Practically numbers of match filters required are more. The signal is passed to match filters of SSS to detect the transmitted $N_{ID}^{(1)}$.

The Figure 7.12 shows output of match filters, where correlation is highest for the $N_{ID}^{(1)} = 5$, was initially transmitted from the base station. Hence, the complete cell ID, frame synchronization is achieved, resulting in downlink synchronization [11].

Figure 7.9. Plot for the slot boundary detection.
Figure 7.10. Match filters for PSS detection.

Figure 7.11. Detected of PSS.
7.4 UPLINK TRANSMISSION

The uplink transmission information can be summarized in the steps shown in Figure 7.13.

MAC layer initiates the random access procedure [12] and has all the information needed for generation of random access preamble such as preamble configuration index, logical root index etc. RA preamble sequence is generated using ZC sequence with length 839 with unrestricted cyclic prefix:

Here the subcarrier spacing is 1.25 KHz and bandwidth = 1.08 MHz, which comes from 1.08 MHz/ 1.25KHz = 864 subcarrier. 12.5 subcarriers are for guard band on either side. Hence, length of cyclic shift is 839.

Using given equations and substituting following parameters:

\[
x_u(n) = e^{-j \frac{\pi}{N_{ZC}}}, \quad 0 \leq n \leq N_{ZC} - 1
\]

\[
x_{u,v}(n) = x_u((n + C_v) \mod N_{ZC})
\]

\[
C_v = v N_{CS} \quad v = 0, 1 \ldots [N_{ZC}/N_{CS}] - 1
\]

\[
x_u(n) = e^{-j \frac{\pi}{N_{ZC}}}, \quad 0 \leq n \leq N_{ZC} - 1
\]
Figure 7.13. Detailed flow diagram for random access procedure.
With \( N_{CS} = 167 \), five different cyclic shifts at positions multiple of 167 (0, 167, 334, 501 and 668) can be generated (see Figure 7.14). The \( 167 \times (0.8 \text{ms} / 839) = 159.23 \) microseconds of delay spread can be supported by configuration 13, assuming preamble format 0.

Taking another example with configuration 7, having

\[
\begin{align*}
N_{ZC} &= 839 \\
N_{CS} &= 22
\end{align*}
\]

Here the available number of cyclic shifts is higher compared to configuration 13 (Figure 7.15). It can support up to \( (22 \times 0.8 \text{ms}) / 839 = 21 \) microseconds of delay spread [8]. This delay spread is directly proportional to the cell size of the system. As cell size increases, the round trip time increases, which in turns increases the need for system to compensate the
delay spread. As the cell size increases, the number of available cyclic shifts decreases; hence, there is a need to use different root sequence to generate the remaining preambles.

The unrestricted cyclic shifts do not take into account the frequency error or effects of high Doppler shifts caused by high-speed movement of UE. It works well when frequency error is low or zero. But when there is an increase in Doppler spread [2], it can lead to wrong detection of a transmitted signal or causes inevitable false alarm.

If the UE is travelling at a high speed, which has high Doppler spread, some restrictions in selecting the cyclic shifts are applied. This type of cyclic shifts is known as restricted cyclic shifts. Restricted cyclic shifts takes care of erroneous delay and is also used to detect positive and negative Doppler spread due to which the correct timing of the symbol cannot be estimated. Therefore some of the cyclic shifts are restricted for sequence generation. Hence not all multiple numbers of cyclic shifts are used but just some of them, which result in no false alarm or ambiguity of positive or negative shifts.

An example of restricted cyclic shifts is discussed.

With parameters defined as:

- Root index $u = 631$
\[ N_{ZC} = 839 \]  
\[ N_{CS} = 18 \]

With given parameters only 12 cyclic shifts (see Figure 7.16) are generated compared with 55 unrestricted cyclic shifts. In restricted cyclic shifts, the number of available cyclic shifts is greatly reduced. The restricted CS depends on the root index \( u \) as well as \( N_{CS} \), but unrestricted CS depends only on \( N_{CS} \).

Figure 7.16. Plot for restricted cyclic shift using \( N_{cs} = 18 \) and \( u = 631 \).
CHAPTER 8

CONCLUSION

This thesis first discussed the modulation techniques used in LTE system, OFDMA as a downlink and SC-FDMA as an uplink. OFDMA is used as downlink access as it supports the flexible bandwidth, low complexity, simple frequency domain equalizer, and high data rates. But due to its high PAPR property, makes it bad candidate for the uplink transmission. SC-FDMA is an ideal candidate, as uplink because it incorporates all the advantages of the OFDMA, yet has relatively low PAPR compared to OFDMA.

The cell search information is transmitted in center 1.08 MHz bandwidth, so the UE can extract synchronization signal and broadcast information of the cell without prior knowledge of the system bandwidth. This makes the UE to detect the system information quickly and effectively. The UE is downlink synchronized (i.e. time and frequency are synchronized).

Random Access (RA) procedure is used for uplink synchronization. As users are at different distances from the base station, there is frame arrival timing uncertainty at the base station, which is taken care of by using the guard time (GT). GT depends on cell size: larger cell has larger GT compared to small GT for smaller cell size to reduce unnecessary overhead. Uplink transmission uses CP to exploit its frequency domain equalization. RA uses RA preambles for detecting the timing uncertainty. These are generated using Zadoff-Chu sequence, which exhibits low PAPR necessary for uplink transmission.

User equipment is uplink and downlink synchronized to receive or transmit the data. All simulations were carried out using MATLAB.
REFERENCES


APPENDIX

SAMPLE CODE
clc
close all
clear all

%%%%
% % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % %
% % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % %
% Primary Synchronization
% Signal
% % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % %
% % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % %
PSS is selected and Matched randomly
% % % % % % % % % % % % % % % % % % % % % % % % % % % %

du_flag_25 = 0;
du_flag_29 = 0;
du_flag_34 = 0;

Nid2 = floor(3*rand); % Selects Nid(2)--- 0,1,2
switch Nid2
    case 0
        du_flag_25 = 1;
    case 1
        du_flag_29 = 1;
    case 2
        du_flag_34 = 1;
end

u25=25;

for n= 0 : 30
    duu_25(n+1) = exp(-j*pi*u25*n*(n+1)/63);
end

for n= 31 : 62
    duu_25(n+1) = exp(-j*pi*u25*(n+2)*(n+1)/63);
end

du_25(1:31)        = duu_25(1:31);
du_25(33:64)       = duu_25(32:63);

for n=0:63
    shift_25(n+1) =du_25(n+1) *exp((j*2*pi*0*n)/63);
end
corr_25=corr_25/max(corr_25);
%%% 
u29=29;

for n= 0 : 30
    duu_29(n+1) = exp(-j*pi*29*n*(n+1)/63);
end

for n= 31 : 62
    duu_29(n+1) = exp(-j*pi*29*(n+2)*(n+1)/63);
end

%%%Putting off data from dc zero frequency index subcarrier %%%% 

du_29(1:31)        = duu_29(1:31);
du_29(33:64)       = duu_29(32:63);

for n=0:63
    shift_29(n+1) =du_29(n+1) *exp((j*2*pi*0*n)/63);
end

[corr_29 lag_29] = xcorr((du_29));

corr_29=corr_29/max(corr_29);

%%% 

%u34=34;

for n= 0 : 30
    duu_34(n+1) = exp(-j*pi*34*n*(n+1)/63);
end

for n= 31 : 62
    duu_34(n+1) = exp(-j*pi*34*(n+2)*(n+1)/63);
end

%%%Putting off data from dc zero frequency index subcarrier %%%% 

du_34(1:31)        = duu_34(1:31);
du_34(33:64)       = duu_34(32:63);

for n=0:63
    shift_34(n+1) =du_34(n+1) *exp((j*2*pi*0*n)/63);
end

[corr_34 lag_34] = xcorr((du_34));

corr_34=corr_34/max(corr_34);

%%% 

figure(1)
subplot(3,1,1)
plot(lag_29,abs(corr_29));
title('u=25');

%%%
grid on
subplot(3,1,2)
plot(lag_29,abs(corr_29));
title('u=29');
grid on
subplot(3,1,3)
plot(lag_34,abs(corr_34));
title('u=34');
grid on
figure(2)
plot(lag_25,abs(corr_25),':r');
grid on
hold on
plot(lag_29,abs(corr_29),'-b');
hold on
plot(lag_34,abs(corr_34),'-g');
hold off
legend('u=25','u=29','u=34');

figure(3)
[cross_25_29 lag_25_29] = xcorr(shift_25,shift_29);
cross_25_29 = cross_25_29 / max(corr_25);%(cross_25_29);
plot(lag_25_29,abs(cross_25_29),'-r');
grid on
hold on
[cross_29_34 lag_29_34] = xcorr(shift_29,shift_34);
cross_29_34 = cross_29_34 / max(corr_25);%(cross_29_34);
plot(lag_29_34,abs(cross_29_34),'-b');
hold on
[cross_25_34 lag_25_34] = xcorr(shift_34,shift_25);
cross_25_34 = cross_25_34 / max(corr_25);%(cross_25_34);
plot(lag_25_34,abs(cross_25_34),'-g');
hold off
legend('u=25 & 29','u=29 & 34','u=34 & 25');
title('Cross Correlation between pairs of Primary Synchronization Signals')