INVESTIGATION OF CHANNELIZER PERFORMANCE TO SYNCHRONIZE UNCOORDINATED FUTURE LTE UPLINK 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
S. M. Shibbir Alam
Spring 2016
SAN DIEGO STATE UNIVERSITY

The Undersigned Faculty Committee Approves the
Thesis of S. M. Shibbir Alam:

Investigation of Channelizer Performance to Synchronize Uncoordinated Future LTE Uplink System

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

Santosh Nagaraj
Department of Electrical and Computer Engineering

Samuel Kassegne
Department of Mechanical Engineering

12-February-2016
Approval Date
Copyright © 2016
by
S. M. Shibbir Alam
All Rights Reserved
DEDICATION

Dedicated to my family and friends.
ABSTRACT OF THE THESIS

Investigation of Channelizer Performance to Synchronize Uncoordinated Future LTE Uplink System

by

S. M. Shibbir Alam

Master of Science in Electrical Engineering

San Diego State University, 2016

Standard LTE system follows random access procedure to coordinate uplink transmission from mobile to base station. The users are at different distances from the cell site and all the signals must arrive at the same time at the cell site for proper demodulation. The cell site performs the reverse control to tell the users to advance or retard their transmission time depending on their distance from the base station so that all the signals can arrive at the same time.

Demand for mobile wireless services continues to explode and in future wireless communications, the network capacity will be increased many times over the current capacity and there will be many more users competing for resources. Current coordination process in the standard LTE uplink system may not be effective to handle future wireless communication system. This thesis proves that implementing polyphase channelizer at the base station provides more efficient way of synchronization eliminating the need of time alignment procedure. Each channel of the channelizer is independent of each other and the occupied signals in different channelizer channels can be demodulated separately without affecting other channels. We have investigated channelizer performance to demodulate both narrow and wide band signals in the LTE uplink system and it is demonstrated that even though the narrow or wide band OFDM signals arrive at the cell site with timing or frequency offset or different channel gains, they can be demodulated independently from different channelizer bins without breaking the orthogonality.
TABLE OF CONTENTS

PAGE

ABSTRACT ...........................................................................................................................................v
LIST OF TABLES ..................................................................................................................................viii
LIST OF FIGURES ................................................................................................................................. ix
ACKNOWLEDGEMENTS .................................................................................................................... xiii

CHAPTER

1 INTRODUCTION .................................................................................................................................1
   1.1 Evolution of Mobile Wireless Communication .................................................................1
   1.2 Thesis Motivation and Outlines ............................................................................................1

2 LTE (LONG TERM EVOLUTION) ..................................................................................................3
   2.1 Overview of LTE Architecture ............................................................................................3
   2.2 LTE Physical Layer .................................................................................................................5
       2.2.1 Multiple Access Techniques .........................................................................................5
       2.2.2 Physical Layer Parameters ............................................................................................7
       2.2.3 LTE Physical Channels ..................................................................................................9
           2.2.3.1 Downlink Physical Channels ....................................................................................9
           2.2.3.2 Uplink Physical Channels .......................................................................................10
       2.2.4 Reference Signals ...........................................................................................................10
       2.2.5 Synchronization Sequences ............................................................................................11

3 SYNCHRONIZATION .....................................................................................................................13
   3.1 Coordination in Standard LTE Uplink System .................................................................13
   3.2 Effect of Time Alignment Failures in LTE Uplink System ..............................................15

4 POLYPHASE FILTER BANK ANALYSIS IN SYNCHRONIZING OFDM SIGNALS .................................................................................................................................................22
   4.1 Standard 1-to-M Up Converter and M-to-1 Down Converter Polyphase Channelizer ........23
4.2 2-to-32 Up Converter and 32-to-2 Down Converter Channelizer Implementation ..................................................................................................................24

4.2.1 Performance of Channelizer to Synchronize Narrow Band
OFDM Signals in LTE Uplink System ..................................................................29

4.3 Timing, Frequency Offset and Channel Estimation ..................................47

4.4 Channelizer Implementation for Both Narrow and Wide Band OFDM
Channels ..................................................................................................................50

4.4.1 Performance of Channelizer to Synchronize both Narrow and
Wide Band OFDM Channels .................................................................................55

5 CONCLUSION ........................................................................................................67

5.1 Summary of the Thesis ..................................................................................67

5.2 Future Works ..................................................................................................67

REFERENCES ..........................................................................................................69
LIST OF TABLES

Table 2.1. Physical layer parameters in downlink FDD LTE [5] .................................................9
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Architecture for 3GPP access networks. [4]</td>
<td>4</td>
</tr>
<tr>
<td>2.2</td>
<td>OFDM subcarrier spacing. [5]</td>
<td>6</td>
</tr>
<tr>
<td>2.3</td>
<td>Transmitter and Receiver structure for SC-FDMA. [6]</td>
<td>7</td>
</tr>
<tr>
<td>2.4</td>
<td>Transmitter and Receiver structure for OFDMA. [6]</td>
<td>7</td>
</tr>
<tr>
<td>2.5</td>
<td>FDD LTE Type 1 Frame Structure. [5]</td>
<td>8</td>
</tr>
<tr>
<td>2.6</td>
<td>Structure of LTE OFDM Symbol. [5]</td>
<td>8</td>
</tr>
<tr>
<td>2.7</td>
<td>Primary and Secondary synchronization symbols in a LTE frame. [5]</td>
<td>12</td>
</tr>
<tr>
<td>3.1</td>
<td>Timing alignment in the standard LTE uplink system[7].</td>
<td>14</td>
</tr>
<tr>
<td>3.2</td>
<td>2048 point OFDM power spectrum from modulator-1.</td>
<td>15</td>
</tr>
<tr>
<td>3.3</td>
<td>2048 point OFDM power spectrum from modulator-2.</td>
<td>16</td>
</tr>
<tr>
<td>3.4</td>
<td>Real part of the demodulated composite signal and the signal constellation</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>from two receivers (no channel, no timing and frequency offset).</td>
<td></td>
</tr>
<tr>
<td>3.5</td>
<td>Real part of the demodulated composite signal and the signal constellation</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>from two receivers (with channel, no timing and frequency offset).</td>
<td></td>
</tr>
<tr>
<td>3.6</td>
<td>Real part of the demodulated composite signal and the signal constellation</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>from two receivers (with frequency offset (0.02%) in signal-2, no channel</td>
<td></td>
</tr>
<tr>
<td></td>
<td>and timing offset).</td>
<td></td>
</tr>
<tr>
<td>3.7</td>
<td>Two OFDM signals are in offset in time.</td>
<td>18</td>
</tr>
<tr>
<td>3.8</td>
<td>Time series from the two OFDM modulator with timing offset.</td>
<td>19</td>
</tr>
<tr>
<td>3.9</td>
<td>Real part of the demodulated composite signal and the signal constellation</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>from two receivers (with timing offset in signal-2, timing delay &lt; CP length)</td>
<td></td>
</tr>
<tr>
<td>3.10</td>
<td>Real part of the demodulated composite signal and the signal constellation</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>from two receivers (with timing offset in signal-2, timing delay &gt; CP length)</td>
<td></td>
</tr>
<tr>
<td>4.1</td>
<td>Standard 1-to-M up converter polyphase channelizer. [9]</td>
<td>23</td>
</tr>
<tr>
<td>4.2</td>
<td>Standard M-to-1 down converter polyphase channelizer. [9]</td>
<td>24</td>
</tr>
<tr>
<td>4.3</td>
<td>Impulse response and frequency response of the prototype low pass filter</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>for Synthesis Channelizer.</td>
<td></td>
</tr>
</tbody>
</table>
Figure 4.4. Impulse and frequency response of the prototype low pass filter and frequency response of three adjacent channel bands for Analysis Channelizer. ........................................25

Figure 4.5. 32 path Synthesis and Analysis channelizer channel spectra and zoom to pass band ripples ...........................................................................................................26

Figure 4.6. 2-to-32 up-sampler in 32-path Channelizer (Synthesis Channelizer). ..................26

Figure 4.7. 32-to-2 Down-sampler in 32-Path Analysis Channelizer. ....................................27

Figure 4.8. Time and frequency response at the synthesis channelizer output when the input is an impulse. ...........................................................................................................28

Figure 4.9. Impulse response of the 15 channels from the 32-path analysis channelizer. .................................................................................................................................29

Figure 4.10. Frequency response of the 15 channels from the 32 path analysis channelizer. .................................................................................................................................29

Figure 4.11. LTE downlink system with three narrow band OFDM channels.....................30

Figure 4.12. LTE uplink system with three narrow band OFDM channels..........................31

Figure 4.13. No timing delay between the arrivals of the signals at the cell site. ..............31

Figure 4.14. Real part of the composite signal time series and spectrum. .........................32

Figure 4.15. 32-to-2 Down Converter Analysis Channelizer output time series (15 channels). ..........................................................................................................................33

Figure 4.16. 32-to-2 Down Converter Analysis Channelizer output spectra (15 channels). .................................................................................................................................33

Figure 4.17. Real part of the demodulated OFDM signal and the signal constellation from bin 18 of the 32-path Analyzer...............................................................34

Figure 4.18. Real part of the demodulated OFDM signal and the signal constellation from bin 22 of the 32-path Analyzer...............................................................34

Figure 4.19. Real part of the demodulated OFDM signal and the signal constellation from bin 14 of the 32-path Analyzer...............................................................35

Figure 4.20. Real part of the composite signal time series and spectrum for three adjacent OFDM signals.................................................................36

Figure 4.21. 32-to-2 Down Converter Analysis Channelizer output spectra (Three adjacent channels). ..............................................................................................................36

Figure 4.22. Demodulated signals from Bin 21, 22 and 23 showing adjacent channels. ......37

Figure 4.23. Signals arriving at the base station at different time due to timing delay in the signals from transmitter 5 and 7.................................................................38

Figure 4.24. OFDM modulation time series with different timing offsets. .......................38

Figure 4.25. Real part of the composite signal time series and spectrum...........................39
Figure 4.26. 32-to-2 Down Converter Analysis Channelizer output spectra (15 channels). ...........................................................39

Figure 4.27. Real part and the signal constellation for the demodulated OFDM signal (QPSK modulated) from Tx-5, with timing offset. ...........................................................40

Figure 4.28. Real part and the signal constellation for the demodulated OFDM signal (16QAM modulated) from Tx-6, no timing delay. ...........................................................40

Figure 4.29. Real part and the signal constellation for the demodulated OFDM signal (16QAM modulated) from Tx-7, with timing offset. ...........................................................41

Figure 4.30. Real part and the signal constellation for the demodulated OFDM signal 1 & 3 after correcting timing offset. ...........................................................41

Figure 4.31. Signals arrive at the cell site at the same time but with a small frequency offset in the signal from Tx-6. ...........................................................42

Figure 4.32. Demodulated OFDM signal -2 having a small frequency offset. ...........................................................42

Figure 4.33. Demodulated OFDM signal -2 from the bin 22 of the channelizer after correcting frequency offset. ...........................................................43

Figure 4.34. Three narrow band signals are passed through three different channels. ...........................................................44

Figure 4.35. Real part of the composite signal time series and spectrum. ...........................................................44

Figure 4.36. 32-to-2 Down Converter Analysis Channelizer output spectra (15 channels). ...........................................................45

Figure 4.37. Demodulated OFDM signals with channel distortions. ...........................................................46

Figure 4.38. Demodulated OFDM signals after correcting channel effects. ...........................................................46

Figure 4.39. Short preamble symbol. ...........................................................47

Figure 4.40. Timing and frequency offset estimation using cross and auto correlation property. [10] ...........................................................48

Figure 4.41. Magnitude of cross-correlation and auto-correlation, normalized cross correlation and angle of the cross correlation. ...........................................................48

Figure 4.42. Long preamble symbol. ...........................................................49

Figure 4.43. Channel frequency response estimate using long preamble. ...........................................................49

Figure 4.44. Impulse response and frequency response of the prototype low pass filter for the 4 path analysis and synthesis channelizer. ...........................................................51

Figure 4.45. 4 path Synthesis and Analysis channelizer channel spectra and zoom to pass band ripples. ...........................................................51

Figure 4.46. Breaking down of wider OFDM signal into narrower channels using 4-to-2 down sampler and then up sampling by 2-to-32 up-converter. ...........................................................52

Figure 4.47. 32-to-2 down conversion and then up sampling by 2 to get original wide bandwidth OFDM signal. ...........................................................53
Figure 4.48. Impulse response of the 4 channels at the output of 4-path analyzer.........54
Figure 4.49. Time and frequency response at the 32-path synthesis channelizer output when the input is an impulse..........................................................54
Figure 4.50. Impulse response of the 15 channels from the 32-path analysis channelizer..........................................................55
Figure 4.51. Time and frequency response at the 4-path synthesis channelizer output........55
Figure 4.52. OFDM modulation time series and spectrum for the wide band and QPSK modulated narrow band signal..........................................................56
Figure 4.53. LTE downlink system with a wide band and two narrow band OFDM channels...........................................................................................................57
Figure 4.54. LTE uplink system with a wide band and two narrow band OFDM channels...........................................................................................................57
Figure 4.55. No timing delay between the arrivals of the signals at the cell site .............58
Figure 4.56. 4-to-2 Down Converter Channelizer output time series and spectra.............59
Figure 4.57. Reassembled wider bandwidth super channel at the 32 path synthesizer output. ...........................................................................................................59
Figure 4.58. Composite signal time series and spectrum..............................................60
Figure 4.59. 32-to-2 Down Converter Analysis Channelizer output time series (15 channels). ...........................................................................................................60
Figure 4.60. 32-to-2 Down Converter Analysis Channelizer output spectra (15 channels). ...........................................................................................................61
Figure 4.61. Output time series from 4-path Synthesizer and assembled signal spectrum...........................................................................................................62
Figure 4.62. Real part and the signal constellation for the demodulated narrow band OFDM signals..........................................................62
Figure 4.63. Real part and the signal constellation for the demodulated wide band OFDM signal...........................................................................................................63
Figure 4.64. Signals arriving at the base station at different time due to timing delay in the signals from transmitter 6 and 7.........................................................63
Figure 4.65. OFDM modulation time series with timing delay in the signals from transmitter 6 and 7. ...........................................................................................................64
Figure 4.66. Demodulated narrow band and wide band OFDM signals that arrive at the cell site at different times..........................................................64
Figure 4.67. Real part and the signal constellation for the demodulated time delayed narrow and wide band OFDM signal after correcting timing offset................65
Figure 4.68. Demodulated narrow band and wide band OFDM signals with frequency offset and after correction..........................................................66
ACKNOWLEDGEMENTS

I would like to extend my gratitude and sincere thanks to my advisor Dr. Fred Harris, for his immense help and infinite patience, for being with me and helping me at every step. And also would like to thank my thesis committee members Dr. Samuel Kassegne and Dr. Santosh Nagaraj for their valuable times.
CHAPTER 1

INTRODUCTION

1.1 EVOLUTION OF MOBILE WIRELESS COMMUNICATION

Mobile wireless communication provides evolutionary paths for people to communicate, as it blends communication with mobility. In a very short span of time remarkable achievements and advancements have already been recorded in the history of wireless communications. Evolution of wireless communication has already embarked on its 4th Generation, when we looked into the past every generation has its own objectives and goals and every new generation has come up with something more advanced [1].

The first generation (1G) of mobile wireless communication utilized analog communication techniques, which were built mainly on frequency modulation (FM) and frequency division multiple access (FDMA). Digital communication techniques emerged from (2G) which were built on time division multiple access (TDMA); the most widely accepted systems of 2nd generation were GSM (Global System for Mobile) and IS-95. The emergence of 3G systems came to the scene when IMT-2000 (International Mobile for Telecommunications-2000) was developed in mid-1980 at ITU (International Telecommunication Union). In the year 2000 two outstanding systems were developed under IMT-2000, WCDMA/UMTS (Wideband CDMA/Universal Mobile Telecommunication System) and CDMA-2000. Both of the above have evolved in to so-called “3.5G”. At present, the Third Generation Partnership Project Long Term Evolution (3GPP LTE) is considered as the path to the next generation of cellular system.

1.2 THESIS MOTIVATION AND OUTLINES

Standard LTE system follows random access procedure to coordinate uplink transmission from mobile to base station. The users are at different distances from the cell
site and all the signals must arrive at the same time at the cell site for proper demodulation. The cell site performs the reverse control to tell the users to advance or retard their transmission time depending on their distance from the base station so that all the signals can arrive at the same time. The user who is far away from the cell site has longer propagation delay than the near user to arrive at the cell site. So the far users will have time advancement compared to the near users and all the users should be coordinated properly so that their signals arrive at the base station at the same time. Demand for mobile wireless services continues to explode and in future wireless communications, the network capacity will be increased many times over the current capacity and there will be many more users competing for resources. Current coordination process in the standard LTE uplink system may not be effective to handle future wireless communication system. This motivates us to implement polyphase channelizer in the base station which provides more efficient way of synchronization to deal with challenges in the future wireless communication system.

The thesis is organized accordingly, with Chapter 2 giving the general overview of the LTE architecture and physical layer. Chapter 3 describes the current coordination process in the standard LTE uplink system and also examines the effects in case of coordination failures in future systems. Chapter 4 presents use of the polyphase analysis channelizer to synchronize OFDM signals. We include considerations of channelizer implementation and performance to demodulate both narrow and wide band signals in the LTE uplink system. Chapter 5 is the summary and conclusion based on the study and future directions.
CHAPTER 2

LTE (LONG TERM EVOLUTION)

The Long Term Evolution (LTE) is the standard for mobile communication which is defined by 3rd Generation Partnership Project (3GPP) to meet up with the set requirements for present and future needs of mobile communications [2]. They offer significant improvements in terms of spectrum efficiency, delay and bandwidth scalability, thanks to the simple architecture design and the use of the Orthogonal Frequency Division Multiplexing (OFDM) based access techniques in the physical layer. LTE offers to meet some of the requirements which include:

- Reduction of delays, specifically on latency
- Significant user data rates increment
- Increased in cell edge bit rate
- Reduction in cost per bit
- Improvement in spectral efficiency
- Flexible network architecture
- Power consumption reduction for user equipment

In this chapter an overview of LTE architecture and LTE physical later is provided.

2.1 OVERVIEW OF LTE ARCHITECTURE

The major components of the LTE System Architecture are [3]

- User Equipment (UE)
- Radio Access Network (RAN)
- Evolved Packet Core (EPC)

The Evolved Packet System (EPS) is comprised of the LTE Radio Access Network and Evolved Packet Core (EPC ⇒ RAN + EPS). At the high level, the LTE network is composed of the Core Network (CN), also called the EPC while there is also the Access
Network called E-UTRAN. Figure 2.1 shows the basic overall system architecture with corresponding functional domains. The four major domain divisions are E-UTRAN, Services, EPC and UE.

![Architecture for 3GPP access networks.](image)

**Figure 2.1. Architecture for 3GPP access networks. [4]**

The UE, EPC and the E-UTRAN are the integral part that formed the Internet Protocol Connectivity Layer, which is also referred to the EPS. The EPS provides the IP based connectivity services, with all services offered at the top of the IP layer.

The Core Network (also known as EPC) does the total control of the UE and establishes the bearers. The CN has a number of different logic nodes, some of which are
Mobility Management Entity (MME)
Packet Data Network (PDN) Gateway (P-GW)
Serving Gateway (S-GW)
Evolved Serving Mobile Location Centre (E-SMLC)
Policy and Charging Rules Function (PCRF)
Home Subscriber Service (HSS)

The MME is the primary control node in the EPC. The control plane information coming from the eNodeB is mainly routed to the MME. The P-GW serves as the end point intermediary router between the external networks and EPS. It mainly provides IP connection at its active point. The S-GW is responsible for the U-plane tunnel management and switching; it acts as the mobile anchor between EPC and the LTE RAN. The E-SMLC is responsible for the management of all the coordination and resource scheduling needed for UE locations in connection with the E-UTRAN. The PCRF is responsible for the QoS as well as the decision making for the policy control. The HSS is a database that contains all users’ subscription details.

2.2 LTE PHYSICAL LAYER

Orthogonal frequency division multiplex (OFDM) is considered as the foundation of the LTE physical layer as the system has to meet certain requirements like high spectral efficiency, high transmission rate and wider channel bandwidths [5]. Second and third generation mobile systems are based either on TDMA or on CDMA technologies. There are some practical limitations to extend these technologies for next generation high data rate wireless systems, whereas OFDM makes the implementation simple and reliable.

2.2.1 Multiple Access Techniques

The multiple access technique in LTE is established on Frequency Domain Multiplexing (FDM). Orthogonal Frequency Domain Multiple Access (OFDMA) is implemented in downlink transmission and Single Carrier Frequency Domain Multiple Access (SC-FDMA) is employed in uplink transmission [5]. The OFDMA uses smaller frequency bands that are dedicated to sub-carriers and they transmit at low power, unlike full transmission for the whole frequency band. The OFDMA provides good system performance
with desired high data rates. In this scheme, the spectrum is basically divided into a series of uniformly spaced orthogonal narrowband sub-carriers; with each sub-carrier spaced at 15 KHz and with corresponding modulation symbols. For 1 symbol duration, a number of sub-carriers are transmitted orthogonally in the frequency domain.

Figure 2.2 shows OFDM orthogonal subcarriers in frequency domain.

![Figure 2.2. OFDM subcarrier spacing. [5]](image)

Additionally, to overcome the problem of Inter Symbol Interference (ISI), a guard interval is inserted between symbols to absorb the transients due to the channel impulse response. Further to preserve the subcarrier orthogonality in the presence of the channel impulse response, a Cyclic Prefix (CP) is inserted in the guard interval at the beginning of the each Orthogonal Frequency Division Multiplexing (OFDM) symbol.

Single carrier FDMA shows better PAPR performance than OFDMA and hence LTE employs SC-FDMA for the uplink and OFDMA for the downlink wireless transmission system. In SC-FDMA, modulation symbols are converted from time domain to frequency domain by an N-point DFT. Then these frequency domain samples are mapped into M-point subcarriers and after that these subcarriers are converted back to time domain samples by a 2M-point IDFT.

The larger size IDFT performs the equivalent of 1-to-2 interpolation of the original time samples. The interpolation function is seen to be the periodic extension of the sinc function, the Dirichlet kernel. The main lobes of successive offset sinc functions only overlap their adjacent neighbors hence their sums are smaller than the sums of overlapped sinusoids.
of OFDMA. Transmitter and receiver structure for SC-FDMA and OFDMA are shown in Figure 2.3 and 2.4.

![Diagram of SC-FDMA](image)

**Figure 2.3. Transmitter and Receiver structure for SC-FDMA. [6]**

![Diagram of OFDMA](image)

**Figure 2.4. Transmitter and Receiver structure for OFDMA. [6]**

### 2.2.2 Physical Layer Parameters

Each radio frame has 10 millisecond of length and each frame is subdivided into 10 sub-frames of one millisecond length. Each sub-frame includes 2 slots of half millisecond length. There can be 7 or 6 OFDM symbols in one slot based on the length of cyclic prefix. The cyclic prefix can be one of two lengths, the longer CP is used when the channel impulse response is longer. The lengthened impulse response occurs when the signal path between platforms is longer. Figure 2.5 presents the FDD LTE frame structure and Figure 2.6 shows the structure of the LTE OFDM symbol.
The basic time unit for LTE is defined based on the 0.72 MHz sample clock for 2048 point FFT. It is calculated as $T_s = \frac{1}{15000 \times 2048} = \frac{1}{30720000}$ seconds. In the normal mode, 7 OFDM symbols are used and the CP length in the first symbol will be $160 \times T_s = 5.2 \mu s$ and for rest of the symbols $T_c p = 144 \times T_s = 4.7 \mu s$. In the extended mode, one slot consists of 6 symbols where $T_c p = 512 \times T_s = 16.7 \mu s$ for all the symbols. For the applications that require high data rate transmission, normal mode is used and the extended mode is utilized for low data rate applications and multi-cell broadcasting. Table 2.1 represents few parameters for the downlink physical layer in FDD LTE mode.
Table 2.1. Physical layer parameters in downlink FDD LTE [5]

<table>
<thead>
<tr>
<th>Bandwidth of Channel (MHz)</th>
<th>1.25</th>
<th>2.5</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration of Frame (ms)</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Duration of Sub-Frame (ms)</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sub-carrier Spacing (kHz)</td>
<td>15</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sampling Frequency (MHz)</td>
<td>1.92</td>
<td>3.84</td>
<td>7.68</td>
<td>15.36</td>
<td>23.04</td>
<td>30.72</td>
</tr>
<tr>
<td>FFT length</td>
<td>128</td>
<td>256</td>
<td>512</td>
<td>1024</td>
<td>1536</td>
<td>2048</td>
</tr>
<tr>
<td>Occupied Sub-carriers</td>
<td>76</td>
<td>151</td>
<td>301</td>
<td>601</td>
<td>901</td>
<td>1201</td>
</tr>
<tr>
<td>Guard Bands</td>
<td>52</td>
<td>105</td>
<td>211</td>
<td>423</td>
<td>635</td>
<td>847</td>
</tr>
<tr>
<td>Resource Blocks</td>
<td>6</td>
<td>12</td>
<td>25</td>
<td>50</td>
<td>75</td>
<td>100</td>
</tr>
<tr>
<td>Bandwidth of Occupied Channel(MHz)</td>
<td>1.14</td>
<td>2.27</td>
<td>4.52</td>
<td>9.02</td>
<td>13.52</td>
<td>18.02</td>
</tr>
<tr>
<td>OFDM Symbols in each sub-frame</td>
<td>Short CP- 7, Long CP-6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length of CP–Normal Mode (μs)</td>
<td>For the1st symbol - 5.2, 6 following symbols - 4.69</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length of CP–Extended Mode (μs)</td>
<td>16.67</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.2.3 LTE Physical Channels

2.2.3.1 DOWNLINK PHYSICAL CHANNELS

For downlink, LTE physical channels include control or transport channels to carry information from higher layers. [5]

There are three transport channels namely Physical Broadcast Channel (PBCH), Physical Downlink Shared Channel (PDSCH) and Physical Multicast Channel (PMCH). PBCH carries 14 bits long Master Information Block (MIB) which consists some parameters needed for initial cell access. The broadcasted parameters are detected by the users at the early stage. PDSCH carries user’s data in downlink LTE system. This channel is also responsible for bearing paging messages and other broadcast information which is not transported by PBCH. PMCH is responsible to provide Multimedia Broadcast and Multicast
Services (MBMS). It is sent in different sub-frames where no PDCH transmission takes place.

The control channel gives different control information and generally in a sub-frame it occupies initial one, two or three OFDM symbols. Physical Downlink Control Channel (PDCCH) provides control information to the users for the efficient data transmission. The control information consist of resource assignments for the users. Physical Control Format Indicator Channel (PCFICH) consists of Control Format Indicator (CFI) that conveys the number of symbols that are used in each sub-frame for the Physical Downlink Control Channel (PDCCH). Physical Hybrid ARQ Indicator Channel (PHICH) carries acknowledgement information (hybrid automatic repeat request (HARQ)) to the users to indicate if the base station has got the uplink signals from the users correctly.

2.2.3.2 UPLINK PHYSICAL CHANNELS

For uplink transmission, LTE system includes three physical channels [5]. Physical Uplink Shared Channel (PUSCH) carries user data in uplink from UE to the base station. It’s responsibilities are comparable to the Physical Downlink Shared Channel (PDSCH). Physical Uplink Control Channel (PUCCH) provides uplink control information which is similar to the control information carried by Physical Downlink Control Channel (PDCCH). For the same user PUCCH is not transmitted at the same time with PUSCH. Physical Random Access Channel (PRACH) helps timing synchronization for the users with the base station. Physical Random Access Channel carries preamble from a user to estimate the timing offset that is needed for the synchronization with the cell site.

2.2.4 Reference Signals

Reference signals help in estimation of the channel and are known to transmitter and receiver. In the LTE system there are two kinds of reference signals in uplink and downlink transmission [5]. Uplink reference signal is transported from mobile to the cell site and downlink reference signal is transmitted to the downlink direction (from cell site to mobile).

Downlink reference signals are transmitted to assist the users in performing channel estimation and demodulation of control and data information, and for channel information measurements. Three kinds of downlink reference signals are available-cell-specific,
MBSFN and dedicated reference signals. Cell-specific reference signals are common to all
users, while UE-specific reference signals are utilized only with dedicated reference-symbol-
based beamforming. MBSFN reference signals are useful in MBSFN transmission and are
common to all cells in the MBSFN service area.

In LTE uplink, there are two types of reference signals, the Demodulating Reference
Signal (DMRS) and Sounding Reference Signal (SRS). DMRS uses the same
bandwidth as the data and its main purpose is to enable coherent demodulation of the
signal at the base station (eNodeB). SRS is an optional feature and is used for aiding
scheduling purposes like channel dependent scheduling.

2.2.5 Synchronization Sequences

A terminal in an LTE system must follow a certain procedure to establish connection
with the network [5]. This procedure includes searching and selection of the cell, extraction
of the information about the system and random access and is generally termed as LTE initial
access. As soon as an LTE terminal is switched on it measures and keeps a list of the signal
from the neighboring cells so as to choose one among them as its serving cell site. Once the
serving cell site is selected, the User Equipment (UE) must remain synchronized to its
serving Base Station (BS) in time to extract the information of the system transmitted to it.
Cell search and synchronization in LTE are performed using primary and secondary
synchronization signals.

The primary and secondary synchronization signals are crucial in LTE cell search and
frame timing synchronization procedures. The primary signals are used to perform the timing
synchronization between the BS and UE. Once the timing synchronization is achieved using
the primary signals, the secondary synchronization signals can be utilized to determine frame
timing and the cell group IDs for the detection of a cell in the network. The secondary signals
are always transmitted one symbol period prior to the primary signal as shown in Figure 2.7.
Primary and Secondary synchronization symbols in a LTE frame. [5]
CHAPTER 3

SYNCHRONIZATION

Synchronization is one of the most important tasks of the wireless communication receivers. When the signals are received at the receiver, all of them should be properly synchronized in order to be demodulated correctly. OFDM signals, based on the orthogonality among subcarrier signals, are more vulnerable to the synchronization problem than the single carrier signals. These signals may face unknown timing delay, frequency offset, channel gain, noise, multipath effects and so on. Some of these unknown parameters change continuously and some of these can be changed slowly and remain unchanged during transmission of an OFDM packet. Proper frequency, timing offset and channel estimation is necessary for the demodulation of the signals. In the standard LTE downlink system, the base station transmits the received signals simultaneously and a handshake can take place between the base station and the recipients that informs the receiver to extract its center frequency of interest. Our main challenge is the LTE uplink system where the users are located at different distances from the base station and all the signals must arrive at the cell site at the same time. In future wireless communications, the network capacity will be increased many times than the current capacity and there will be many more users competing for resources. Current coordination process in the standard LTE uplink system may not be effective to handle future wireless communication system.

In this chapter standard coordination process in the LTE uplink system is explained and also some situations are analyzed to demonstrate the effects of coordination failure.

3.1 COORDINATION IN STANDARD LTE UPLINK SYSTEM

Standard LTE system follows random access procedure to coordinate uplink transmission from mobile to base station. The users are at different distances from the base station and all the signals must arrive at the same time at the base station for proper demodulation. The cell site performs the reverse control to tell the users to advance or retard
their transmission times depending on their distance from the base station so that all the signals can arrive at the same time. The user who is far away from the cell site has longer propagation delay than the near user to arrive at the cell site. So the far users will have time advancement comparing to the near users and all the users should be coordinated properly so that they can arrive at the base station at the same time with no frequency offset and same power level.

As an example let us consider one user U1 is located far from the base station and another user U2 is near to the base station. If the propagation delay for the downlink transmission from cell site to U1 and U2 are $d_1$ and $d_2$ respectively, the transmitted subframe at time $t_1$ from the cell site will be seen by U1 at time $t_1 + d_1$ and U2 will get that at time $t_1 + d_2$. For the timing alignment at the base station, U1 should start its uplink transmission at $t_1 + 2d_1$ and U2 should start at $t_1 + 2d_2$. Figure 3.1 represents the time alignment process.

![Diagram showing timing alignment in the standard LTE uplink system][7].
The cell site needs to adjust the timing for the uplink transmission continuously for the proper coordination of all transmissions and any failure in the coordination would cause severe degradation in the signals.

3.2 Effect of Time Alignment Failures in LTE Uplink System

To explain the scenario of an uncoordinated LTE uplink system where the signals arrive at the cell site at different times with frequency offsets and different channel gains, first I am going to present a system where there’s no channel gain and carrier or timing offset with the signals. Two OFDM modulator is formed each having 48 point transforms. The first modulator modulates only positive frequencies (bin +1 to +16) where each bin is modulated by 16QAM and the second modulator is formed by QPSK modulation in negative frequency bins (bin -1 to -16). Both modulators have OFDM packet consisting 40 OFDM symbols and cyclic prefix is taken from the last 12 samples of the OFDM symbol.

Figure 3.2 and 3.3 shows time series 2048 point OFDM power spectrum from the modulator-1 and modulator-2.

![Figure 3.2. 2048 point OFDM power spectrum from modulator-1.](image-url)
Let us consider there’s no channel gains and timing or frequency offset with the OFDM signals and both the signals have arrived at the cell site at the same time and added together. Receiver-1 and receiver-2 have demodulated the signals from modulator-1 and modulator-2 respectively.

In Figure 3.4 the upper subplot shows the overlaid real part of all the transforms of the demodulated composite OFDM signals and the lower subplot represents (time and frequency) overlaid constellation diagram of the demodulated OFDM signal from the receiver-1 and 2.

So it is obvious that when the signals arrive at the cell site at the same time without any frequency offset or noise or channel gains, all the symbol points will have same phase and gain without smearing into neighboring points. The adjacent bands will not be affected and OFDM signals can be demodulated perfectly without breaking orthogonality.

Now let us think the two OFDM signals pass through two different channels where the impulse responses are \((1 0 0 0 j^{0.2} 0 0 0 0 0 0.1)\) and \((1 0 0 0 0.1 0 0 0 j^{0.1} 0 -0.05)\) respectively. Also in this case the signals will not have any timing or frequency offset. The signals are added together in the free space and from the overlaid plots of the demodulated signal we can observe the signal distortions that are caused by different channel gains.
In the next step the LTE uplink system is investigated with a small frequency offset in one of the OFDM signals without having any timing offset or channels. In this case both the signals have arrived at the cell site at the same time but signal-2 (QPSK modulated) has small frequency offset (0.2%). As shown in the Figure 3.6, small frequency offset causes spinning in the signal samples but the samples do not spill over the adjacent band. Receiver-1 can

Figure 3.4. Real part of the demodulated composite signal and the signal constellation from two receivers (no channel, no timing and frequency offset).

Figure 3.5. Real part of the demodulated composite signal and the signal constellation from two receivers (with channel, no timing and frequency offset).
demodulate the 16QAM modulated signal perfectly maintaining orthogonality but receiver-2 can’t demodulate due to presence of frequency offset in the signal.

Figure 3.6. Real part of the demodulated composite signal and the signal constellation from two receivers (with frequency offset (0.02%) in signal-2, no channel and timing offset).

Figure 3.7 presents a situation where the two OFDM signals have arrived at the cell site at different time.

Figure 3.7. Two OFDM signals are in offset in time.

Figure 3.8 shows the real part of the time series of the two signals where the QPSK modulated OFDM signal from modulator-2 is having 10 samples timing delay which is less than the cyclic prefix length (12 samples).
Figure 3.8. Time series from the two OFDM modulator with timing offset.

As there’s timing delay in the signal-2, transmitter-1 and transmitter-2 starts transmitting at different time. Assume this is an uncoordinated system; the two signals can’t arrive at the base station at the same time. In Figure 3.9 the upper subplot shows the overlaid real part of all the transforms of the demodulated composite OFDM signals and the lower subplot represents (time and frequency) overlaid constellation diagram of the demodulated OFDM signal from the receiver-1 and 2. Due to timing offset in the signal-2, receiver-2 cannot demodulate the OFDM signal with maintaining the orthogonality but the other band with no timing offset still gets unaffected.

If the timing delay is more than the length of the CP, from the demodulated OFDM symbols it can be observed that not only the band for signal-2 gets distorted but also it starts affecting the neighboring band. The symbol points from the negative frequency band start spilling over the adjacent band and it also causes the breaking of orthogonality of OFDM signal-2.
The above discussion gives us a better picture about what would happen if coordination in the standard LTE uplink system fails. In future wireless communications, the network capacity would be increased many times than the current capacity and there would be many more users competing for resources. Current coordination process in the standard
LTE uplink system may not be effective to handle future wireless communication systems. This motivates us to implement polyphase filter banks in future LTE uplink system that offers an efficient way eliminating the need of time alignment process. In the next chapters performance of polyphase channelizer to synchronize uncoordinated future LTE uplink system will be investigated.
CHAPTER 4

POLYPHASE FILTER BANK ANALYSIS IN SYNCHRONIZING OFDM SIGNALS

Partitioning a spectrum using polyphase filter banks can offer numerous benefits and one of them is cost reduction in the system as multichannel processing requires less system resources [8]. A polyphase up converter channelizer performs as a modulator and up samples the input baseband signals of different center frequencies. If the input signal bandwidth is more than the channelizer channel bandwidth, then the signal is processed by a small down-converter before going through the up converter channelizer. Similarly a polyphase down converter channelizer performs as a demodulator where the input frequency domain multiplexed signals are first sampled and then down converted to the baseband.

In this thesis we are going to use 2-to-M up converter synthesis channelizer and M-to-2 down converter analysis channelizer to demonstrate the synchronization process in the LTE system. Each channel in the channelizer is independent of each other and the signals that arrive at the cell site can have timing or frequency offset and unknown channel gains but still can be demodulated perfectly without any coordination requirements. The 2-to-M up converter channelizer can change the input sample rate from 2fs to Mfs where M-to-2 down converter channelizer performs sample rate change from Mfs to 2fs at the output. To demonstrate the channelizer performance in the LTE system, first we need to build the synthesis and analysis channelizers using appropriate prototype filter design. After briefly describing the standard 1-to-M up converter and M-to-1 down converter channelizers, we will discuss the prototype filter design, implementation and performance of the M-to-2 and 2-to-M polyphase channelizer structures in the following sections.
4.1 Standard 1-to-M Up Converter and M-to-1 Down Converter Polyphase Channelizer

Figure 4.1 shows standard 1-to-M up converter polyphase channelizer structure that performs multiple interpolation and digital up-conversions, equivalent to Digital Up Conversion (DUC), in a single process. It consists M-point IFFT, M-path partitioned filter and an M-port commutator [9].

Three basic steps are performed by this standard structure: IFFT performs 1-to-M up sampling and complex phase rotation of the input signal samples, the samples are then shaped by a prototype low pass filter and M-port commutator extracts the M-output samples formed in response to the single samples. This polyphase channelizer is sampled critically with channel spacing, channel bandwidth and input sample rate equal to fs. It is useful for the signal components processed by the channelizer to be sampled at 2-samples per symbol and thus satisfy the Nyquist criterion with a margin to avoid spectral folding at their band edges. This motivates us to use, in our study, 2-to-M up converter synthesis channelizer instead of the standard design.

Figure 4.2 shows standard M-to-1 down converter polyphase channelizer structure that performs multiple digital down conversion (DDC) operations in a single process. It consists M-port commutator, M path partitioned filter and M point IFFT [9].
Three basic steps are performed by this standard structure: M-port commutator performs sample rate reduction, bandwidth reduction is performed by the M-path partitioned filter weights and IFFT performs the selection of the desired Nyquist zone. This channelizer is sampled critically with channel spacing, channel bandwidth and output sample rate equal to Mfs/M or fs. The channel bandwidth, sample rate and spacing are all same for this maximally decimated channelizer. For this reason the transition band edges of the channelizer filter alias onto itself. This motivates us to use M-to-2 down converter channelizer in our study which prevents aliasing at the neighboring channels band edge. In this modified design the output sample rate is doubled without changing the channel spacing or bandwidth.

### 4.2 2-to-32 Up Converter and 32-to-2 Down Converter Channelizer Implementation

The prototype filter for the 32 path synthesis channelizer is designed using remez algorithm. It’s a 223 tap prototype low-pass Nyquist filter and each of the paths in the 32 path filter contains 7 taps per path. It’s side lobe levels are designed to be below -65 dB with in-band ripple 0.002 dB.

To design the prototype filter for the 32 path analysis channelizer, we have used a Kaiser Bessel windowed sinc function. This prototype Nyquist filter has 320 taps and each of the paths in the 32 path filter contains 10 taps per path. The channel spacing is 1 MHz and
sample rate per channel is 2 MHz. The stop band attenuation is below -60 dB and pass band ripples are 0.002 dB. Also the adjacent channels of this filter crosse at their -6 dB levels.

Figure 4.3 and 4.4 present impulse response and frequency response of the prototype low pass filter for the synthesis and analysis channelizer respectively and also the three adjacent channels of the analysis filter.

Figure 4.3. Impulse response and frequency response of the prototype low pass filter for Synthesis Channelizer.

Figure 4.4. Impulse and frequency response of the prototype low pass filter and frequency response of three adjacent channel bands for Analysis Channelizer.
Figure 4.5 shows overlay of pass band ripples and spectrum for the synthesis and analysis prototype filters. The prototype synthesis filter is wider than the prototype analysis filter and both have pass band ripples less than 0.003 dB.

Figure 4.5. 32 path Synthesis and Analysis channelizer channel spectra and zoom to pass band ripples.

The prototype filters designed above will be used in the 32 path polyphase analysis and synthesis filter banks structure. Figure 4.6 shows the structure of the 2-to-32 up-converter synthesis channelizer.

Figure 4.6. 2-to-32 up-sampler in 32-path Channelizer (Synthesis Channelizer).
The baseband signals are delivered to the input of the synthesis channelizer which works as a set of digital up-converters that forms a composite signal by the channelizer process. The bandwidths of the input signals are less than the channelizer filter bandwidth. Here all the input signals will be up sampled and frequency bands will be shifted to selected center frequencies from the baseband. The sample rate at the input can be changed from 2fs to the output sample rate 32fs. The 32 point IFFT performs 1-to-32 up sampling and also complex phase rotation of the input signals. The circular buffer performs the circular shift which simultaneously maintains the correct phase alignments to all frequencies and enables the 50% overlapped of successive output vectors that performs the 2-to1 down sample from the IFFT. The samples are then shaped by a prototype low pass filter.

Figure 4.7 represents 32-path analysis channelizer structure which works as a set of digital down-converters that forms the collection of baseband signals from the LTE uplink system. Signals from different users in the uplink system are added together in free space and are delivered at the input of the analysis channelizer as a composite signal.

![Analysis Channelizer](image)

**Figure 4.7. 32-to-2 Down-sampler in 32-Path Analysis Channelizer.**

This 32-path analysis channelizer works as polyphase 32-to-2 down converter. If the input sampling rate is 32 MHz, then there will be 2 MHz sampling rate for each channel and channel spacing would be 1 MHz. At the same time, 16 samples can be transferred to the 32-
path channelizer through the input commutator but the number of samples at the channelizer output would be 32. The commutator starts delivering first 16 input samples from the middle point of the channelizer i.e. from port 15 to port 0. The next 16 samples are delivered from the same ports while the previous 16 samples are shifted to port 31 to port 16. To maintain time alignment between the shifting origin of the input sequence and the origin of the IFFT a circular buffer is used to shift alternate input blocks 16 samples. The next step is the 32-point IFFT block where the output is phase rotated to the selected Nyquist zones.

To inspect and verify performance of the channelizer, we have delivered an impulse to the channelizer inputs and examined the time and frequency response at the 32-path synthesizer output. We have also examined the time and frequency response of the 15 channels from the 32-path analysis channelizer. These results are shown in the following figures. From the multiple impulse responses we can observe the time offset and phase rotations in the channelizer base banded channels as well as their frequency responses.

Figure 4.8. Time and frequency response at the synthesis channelizer output when the input is an impulse.
Figure 4.9. Impulse response of the 15 channels from the 32-path analysis channelizer.

Figure 4.10. Frequency response of the 15 channels from the 32 path analysis channelizer.

4.2.1 Performance of Channelizer to Synchronize Narrow Band OFDM Signals in LTE Uplink System

To demonstrate the channelizer performance in LTE system, let us consider that three users are talking to three other mobile users through three narrow band OFDM channels. Each OFDM signal bandwidth is less than the channelizer channel bandwidth.
Three OFDM modulators are formed with separate having 64 point transforms. Each of the symbols contains 24 occupied frequency bins with the first modulator bins modulated by QPSK and next two modulator bins modulated by 16QAM. All modulators have OFDM packet consisting 50 OFDM symbols and cyclic prefix is taken from the last 16 samples of their respective symbols. Figure 4.11 and 4.12 represents a scenario where channelizer is implemented at the cell site and three narrow band OFDM channels are communicating in the LTE uplink and downlink system.

Say in the LTE downlink system, three users UE1, UE2 and UE3 are transmitting narrow band OFDM packet to three other users UE5, UE6 and UE7 who are under the same cell coverage. The communication up to the cell site is through backhaul fiber or microwave links and when the cell site receives the data, a 2-to-32 up-sampler synthesis channelizer performs up-sampling of the input signals and their frequency bands translated from baseband to the selected center frequency by the channelizing process.

![Figure 4.11. LTE downlink system with three narrow band OFDM channels.](image)
A handshake can take place between the base station and the recipients that informs the receiver to extract its center frequency of interest. Our main concern is the LTE uplink system when the users located in different distances from the base station start transmitting back. In the uplink system, 32-to-2 down converter channelizer is implemented where the input composite signal have been down sampled and their frequency bands have been translated to base-band by the aliasing channelizing process.

To demonstrate the channelizer performance in the LTE uplink system, first we assume that all the narrow band OFDM channels from transmitter-5, 6 and 7 arrive at the base station at the same time without any frequency offset and channel gains.

Figure 4.12. LTE uplink system with three narrow band OFDM channels.

Figure 4.13. No timing delay between the arrivals of the signals at the cell site.
The signals are added together in the free space and delivered at the input of the 32-to-2 down sampler analysis channelizer. For our simulation purpose, we have used 32 path synthesis channelizer which forms a composite signal translating base band frequencies to the selected center frequencies. Figure 4.14 shows the time series and spectra of the multiple OFDM signals.

Figure 4.14. Real part of the composite signal time series and spectrum.

Figure 4.15 and 4.16 shows the time and frequency response from the 15 channels of the polyphase 32-to-2 analysis channelizer engine. The down converter polyphase channelizer has partitioned the entire spanned frequency range into 32 segments.
Figure 4.15. 32-to-2 Down Converter Analysis Channelizer output time series (15 channels).

Figure 4.16. 32-to-2 Down Converter Analysis Channelizer output spectra (15 channels).

In Figure 4.16 it’s easy to recognize the different spectra comprising the received signal. Bin14 (Channel#-3) , Bin18 (Channel#1) and Bin22 (Channel#5) occupies the three narrow band OFDM signals. All other spectral segments that visible in other bins, are in the
transition bands and will be filtered out by the channelizer demodulation filters. We can demodulate and synchronize each of the sub-channels independent of each other. Figure 4.17, 4.18 and 4.19 represent the demodulated OFDM signal from the bin 18, bin 22 and bin 14 respectively.

Figure 4.17. Real part of the demodulated OFDM signal and the signal constellation from bin 18 of the 32-path Analyzer.

Figure 4.18. Real part of the demodulated OFDM signal and the signal constellation from bin 22 of the 32-path Analyzer.
Here we can see that all of the 16QAM and QPSK constellations map to their appropriate constellation points and all the narrowband OFDM signals are perfectly demodulated maintaining their orthogonality. It proves that when all the signals arrive at the cell site at the same time in the LTE uplink system, the channelizer demonstrates the correct functionality in demodulating the signals without any distortion.

The narrow band OFDM signals that have been discussed so far have empty adjacent channels. In the real world the adjacent channels may not be empty and Figure 4.20 presents the synthesized output time series and spectra when three narrow band OFDM channels are adjacent to each other. Due to three channels being adjacent, some spectral regions to the right and left of the mid band signal are overlapped with their neighbor channels.
Figure 4.20. Real part of the composite signal time series and spectrum for three adjacent OFDM signals.

As seen from the 32-to-2 analysis channelizer output channels in Figure 4.21, three narrow band adjacent channels occupy Bin21, Bin22 and Bin23.

Figure 4.21. 32-to-2 Down Converter Analysis Channelizer output spectra (Three adjacent channels).

Each channel has entered into each other spectral region but they don’t talk to each other in modulation bandwidth but only in the adjacent transition bands. Filters or frequency
FFT selection in the demodulator can separate adjacent spectral bands and select only the modulation bandwidth from the entire interval.

Figure 4.22 shows the demodulated whole spectrum taken from three adjacent output bins of the 32-path analyzer. 16QAM modulated signal from bin 22 observes a part of the adjacent channel spectra from bin 21 and bin 23. Signal from bin 21 and bin 22 also observing a part of the spectral region from the adjacent bin 22.

![Real Part of Demodulated OFDM Signal(QPSK) from Bin 21](image1)

![Real Part of Demodulated OFDM Signal(16QAM) from Bin 22](image2)

![Real Part of Demodulated OFDM Signal(16QAM) from Bin 23](image3)

**Figure 4.22. Demodulated signals from Bin 21, 22 and 23 showing adjacent channels.**

The 32-to-2 down converter channelizer is designed in such a way that it allows the adjacent spectra in the transition bands but doesn’t allow them in the modulation bandwidth. The filters can selectively separate the occupied signal in the modulation bandwidth ignoring the adjacent channels. This demonstrates channelizer ability to demodulate signals having adjacent channels.

Now it would be interesting see the channelizer performance if the time alignment in the standard LTE fails, i.e. if the signals arrive at the cell site at different time. Figure 4.23 shows the scenario when the three narrow band OFDM channels are arriving at the base station at different time. For the simulation purpose we assume there’s no channel distortion or frequency offset to the OFDM signals.
Figure 4.23. Signals arriving at the base station at different time due to timing delay in the signals from transmitter 5 and 7.

From the OFDM modulation time series we can see that signal from the transmitter-5 arrives at the cell site with 50 samples delay and the signal from transmitter-7 experiences shorter 10 samples delay (less than CP).

Figure 4.24. OFDM modulation time series with different timing offsets.

Figure 4.25 shows composite signal time series and spectra presented at the analyzer input.
Figure 4.25. Real part of the composite signal time series and spectrum.

The frequency responses from the 15 channels of the polyphase 32-to-2 analysis channelizer engine in Figure 4.26 show that bin14, bin18, and bin22 still occupy the same narrow band OFDM signals. Figure 4.27, 4.28 and 4.29 represent the demodulated OFDM signal from the bin 18, bin 22 and bin 14 respectively.

Demodulated OFDM signals from the transmitter 5 & 7 show significant degradation in the samples because of the timing delay. On the other hand the receiver can demodulate
the 16QAM modulated signal from the transmitter 6 without any distortion in the samples and orthogonality is also preserved.

Figure 4.27. Real part and the signal constellation for the demodulated OFDM signal (QPSK modulated) from Tx-5, with timing offset.

Figure 4.28. Real part and the signal constellation for the demodulated OFDM signal (16QAM modulated) from Tx-6, no timing delay.
Figure 4.29. Real part and the signal constellation for the demodulated OFDM signal (16QAM modulated) from Tx-7, with timing offset.

Figure 4.30. Real part and the signal constellation for the demodulated OFDM signal 1 & 3 after correcting timing offset.

Preambles can be formed to estimate and correct the timing offsets to synchronize the signals. To check the correct functionality of the channelizer, known delays have been used in demodulation without going through the acquisition process. 50 and 10 samples timing offsets have been used during the demodulation process for the OFDM signal 1 and 3.
respectively and Figure 4.30 represents both the demodulated signal after timing offset correction.

This shows that the signals with the timing delay can be demodulated perfectly from the channelizer channels estimating the correct timing offset.

To investigate the channelizer performance to the signal with frequency offset, OFDM signal from the transmitter 6 has been set with a small frequency offset (0.1%) and all the three narrow band channels are arriving at the cell site at the same time without having any channel gains. Figure 4.31 represents this scenario.

![Figure 4.31. Signals arrive at the cell site at the same time but with a small frequency offset in the signal from Tx-6.](image)

![Figure 4.32. Demodulated OFDM signal -2 having a small frequency offset.](image)
Figure 4.32 shows the demodulated signal from channelizer bin 22 and it is seen that small frequency offset causes spinning in the signal samples.

Preambles can be formed to estimate the rotation rate and to correct the frequency offsets by de-spinning the signal. During the demodulation process, known rate of rotation is used to de-spin the signal samples to verify the channelizer performance.

![Real Part of Demodulated OFDM Signal-2](image1)

![Constellation of Demodulated OFDM Signal-2](image2)

**Figure 4.33. Demodulated OFDM signal -2 from the bin 22 of the channelizer after correcting frequency offset.**

From Figure 4.33 the constellation points looks sharp without any smearing which demonstrates the correct functionality of the channelizer in separating the signal with frequency offset. The separate frequency offsets are resolved and removed by the demodulators following the channelization. Similarly other two signals located at the bin 14 and bin 18 can be demodulated separately without affecting other channelizer channels.

To investigate the channelizer performance when the input signals have different channel gains, three narrow band OFDM signals have been passed through three different channels without having any timing or carrier offset. Figure 4.34 presents the scenario.
The impulse responses of the channel 1, 2 and 3 used for the simulation purposes are $(1 0 0 0 j^*0.2 0 0 0 0 0 1)$, $(1 0 0 0 0.1 0 0 0 0 0 0.1 0 -0.05)$ and $(1 0 0 0.05 0 0 0.05 0 -j^*0.1 0 .05)$ respectively. The signals are added together in the free space and Figure 4.35 shows the composite signal time series and spectra formed by 2-to-32 up-sampler synthesizer.

Figure 4.35. Real part of the composite signal time series and spectrum.
The composite signal is delivered as input to the 32-to-2 analyzer and this down converter polyphase channelizer has partitioned the entire spanned frequency range into 32 segments. This time also the three narrow band signals occupy the same channelizer bins as seen from Figure 4.36 but get some channel distortions.

From the demodulated OFDM signals taken from the channelizer bin 18, 22 and 14 as seen in Figure 4.37 show that signals are distorted due to their different frequency dependent channel profiles.

To correct the distortions from the demodulated data caused by the channel, unknown channel frequency response can be estimated using long preambles and this channel estimation is used to reverse the channel effects. To verify the channelizer performance, known channel frequency response is utilized to get the inverse channel response and signals from the channelizer bins are demodulated using this inverse estimate. Figure 4.38 shows that the channel effects are corrected in all the signals as the demodulated samples look sharp without any smearing.
Figure 4.37. Demodulated OFDM signals with channel distortions.

Figure 4.38. Demodulated OFDM signals after correcting channel effects.

Each channel of the channelizer is independent of each other and the occupied signals in different channelizer channels can be demodulated separately without affecting other channels.
The above discussion proves that even though the OFDM signals arrive at the cell site with timing or frequency offset or different channel gains, they can be demodulated independently from different channelizer bins without breaking the orthogonality. This demonstrates versatility of the channelizer in synchronizing narrow band signals in LTE uplink system.

4.3 Timing, Frequency Offset and Channel Estimation

Each OFDM packet consists preambles which help the receiver in the initial acquisition process. Preamble detection is the initial task of the receiver. The receiver can process the received signal with a replica correlator which is matched to the known short preamble structure.

Figure 4.39 shows a short preamble symbol which consists 12 occupied frequency bins out of 64 point transform where one in four bins are occupied. It also includes cyclic prefix taken from the last 16 samples of the preamble.

![Figure 4.39. Short preamble symbol.](image)

For the detection of the preamble the replica correlator [10] can be built as the cross correlation between input and output of a 16 samples delay line. Using this 16 samples delay line we need to form the cross product between input and output and the auto product at the output and form the running cross and auto correlation via 16-tap box-car averagers. The sample by sample ratio of the cross to the auto correlation functions identifies the start of the OFDM frame.

Before entering into the replica correlator, the short preamble is delayed by 10 samples and a white noise of standard deviation 0.01 is added to it. Then the data is spun at 2.5 degrees per sample. Figure 4.41 shows the magnitude of cross-correlation and auto-correlation and the normalized cross correlation and angle of the cross correlation. The angle
of the cross correlation estimates the frequency offset in the input OFDM signal and this information is used to de-spin the signal samples.

Figure 4.40. Timing and frequency offset estimation using cross and auto correlation property. [10]

Figure 4.41. Magnitude of cross-correlation and auto-correlation, normalized cross correlation and angle of the cross correlation.

Channel estimation is the estimation of the unknown channel frequency response and correcting the distortions from the demodulated data that caused by the channel.
In order to estimate the channel a long preamble symbol is formed which consists 24 occupied frequency bins out of 64 point transform where each bin is QPSK modulated. It also includes cyclic prefix taken from the last 16 samples of the preamble. When the receiver receives this preamble symbol it demodulates it and uses the known spectral values to measure and correct the distortion caused by the channel.

![Spectrum: Long preamble symbol](image)

**Figure 4.42. Long preamble symbol.**

If the signal passes through a channel of impulse response of $(1 \ 0 \ 0 \ 0 \ j^*0.2 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0.1)$, the channel frequency response can be estimated using the relationship between the channel and received signal which is $F_{\text{channel}}=F_{\text{channel\_output}}/F_{\text{channel\_in}}$. Figure 4.43 represents channel frequency response estimate using long preamble.

![Spectrum: Response of long preamble probe and of channel(red)](image)

**Figure 4.43. Channel frequency response estimate using long preamble.**
From the channel estimate we can use the inverse of the channel at each frequency to demodulate the data segment of the symbol frames which will correct the distortions caused by the channel.

**4.4 Channelizer Implementation for Both Narrow and Wide Band OFDM Channels**

In the section 4.2.2 we have explained the scenario where all the signals present at the channelizer input have smaller bandwidths than the channelizer channel spacing. In the real world the signals are not only narrow band but also wide band where bandwidth of the signals extends over multiple channel widths.

For the narrow band OFDM signals same 32-path synthesis and 32-path analysis channelizer engine are used as described in section 4.2.1. To deliver a wide band signal to the input of the 32 path synthesis channelizer, first it has to be disassembled into several segments with the expected sample rate and bandwidth of this channelizer. This decomposition is done by a 4-to-2 analysis channelizer and then these segments are delivered to the 2-to-32 up-converter synthesizer and reassembled into the wider bandwidth super channel.

In the demodulator, the 32-to-2 down converter channelizer partitions the entire frequency range at its input into several segments and all the segments have been aliased to baseband. To recombine the segments of the wide band signal, all the wide band signal fragments are delivered to a 2-to-4 synthesis channelizer where the input time series are up-sampled and translated to their proper spectral region.

To design the prototype filter for the 4 path analysis channelizer, we have used matlab sinc function. This prototype sqrt Nyquist filter has 40 taps and each of the 4 path filter contains 10 taps per path. The channel spacing is 1 MHz and sample rate per channel is 2 MHz. The stop band attenuation is less than -60 dB and pass band ripples are around 0.002 dB. Also the adjacent channel of this filter crosses at -6 dB level.

The prototype filter for the 4 path synthesis channelizer is designed using remez algorithm. It's a 27 tap prototype low-pass sqrt Nyquist filter and each of the 4 path filter contains 7 taps per path. Its side lobe levels are less than -60 dB and in-band ripples are
around 0.002 dB. Figure 4.44 presents impulse response and frequency response of the prototype low pass filter for the 4 path analysis and synthesis channelizer.

![Impulse Response, Prototype Filter for 4-Path Analysis Channelizer](image1)

![Impulse Response, Prototype Filter for 4-Path Synthesis Channelizer](image2)

![Frequency Response, Prototype Filter for 4-Path Analysis Channelizer](image3)

![Frequency Response, Prototype Filter for 4-Path Synthesis Channelizer](image4)

Figure 4.44. Impulse response and frequency response of the prototype low pass filter for the 4 path analysis and synthesis channelizer.

![Zoom to Pass Band Ripple: 4-Path Analysis Channelizer (Blue) & 4-Path Synthesis Channelizer (Red) Spectra](image5)

Figure 4.45. 4 path Synthesis and Analysis channelizer channel spectra and zoom to pass band ripples.
Figure 4.45 shows overlay of pass band ripples and spectrum for the 4-path analysis and synthesis prototype filters. The prototype synthesis filter is wider than the prototype analysis filter and both have pass band ripples less than 0.003 dB.

The prototype filters designed above have been used in the 4 path polyphase analysis and synthesis filter banks structure. To construct 32 path analyzer and synthesizer, we have utilized the same prototype filters that are used for narrow band signal processing.

Figure 4.46 shows the block diagram of polyphase filter bank structure for partitioning a signal of bandwidth wider than the channelizer filter bandwidth by a 4-to-2 analyzer and then reassembling into a wider bandwidth super channel by 2-to-32 synthesizer.

The first 4-to-2 down sampler channelizer partitions the input wide band signal into 4 segments. The commutator starts delivering first 2 input samples from port 1 to port 0. Next 2 samples are delivered from port 3 to port 2. To match the time origin between input and output, circular shift buffer block is used. Next step is 4-point IFFT block where the output is phase rotated. Selected segments from the analyzer output are presented to the input ports of the 2-to-32 synthesis channelizer and the input time series are upsampled, frequency shifted and recombined by the channelizer process.

![Diagram of polyphase filter bank structure](image)

**Figure 4.46.** Breaking down of wider OFDM signal into narrower channels using 4-to-2 down sampler and then up sampling by 2-to-32 up-converter.
Figure 4.47 represents the demodulator structure to process wide band OFDM signal in the LTE uplink system.

![Diagram of demodulator structure](image)

**Figure 4.47. 32-to-2 down conversion and then up sampling by 2 to get original wide bandwidth OFDM signal.**

The polyphase down converter polyphase channelizer simultaneously down samples and down converts the composite received spectrum. A channel selector at the output of the analyzer delivers the wide band signal segments to the 2-to-4 synthesizer input. This synthesizer up samples, translates and reassembles previously fragmented spectral segments and reconstructs the wide band signal.

To inspect the channelizer, we have delivered an impulse to the 4-path analysis channelizer input and the output time series from all the four channels are delivered to the 32-path synthesizer. Figure 4.48 shows the impulse response of the 4 channels at the output of the analyzer and figure 4.49 presents time series and spectra at the synthesizer output.
Figure 4.48. Impulse response of the 4 channels at the output of 4-path analyzer.

Figure 4.49. Time and frequency response at the 32-path synthesis channelizer output when the input is an impulse.

At the demodulator, from the output time series of the 32-to-2 down sampler analyzer, 3 channels are delivered to the 2-to-4 synthesizer and Figure 4.51 shows the synthesizer output time series and spectra. From these impulse responses we can observe the time offset in channelizer channels.
Figure 4.50. Impulse response of the 15 channels from the 32-path analysis channelizer.

Figure 4.51. Time and frequency response at the 4-path synthesis channelizer output.

4.4.1 Performance of Channelizer to Synchronize both Narrow and Wide Band OFDM Channels

To demonstrate the channelizer performance to synchronize both narrow and wider bandwidth channels in LTE system, let us consider that three users are talking to three other mobile users through two narrow and a wide band OFDM channels. Each narrow band
OFDM signal bandwidth is less than the channelizer channel bandwidth and the wide band signal has bandwidth more than the channelizer channel spacing.

The wide band OFDM signal is formed with a 128 point transform where each symbol consists 48 occupied frequency bins and modulated by 16QAM. Cyclic prefix is taken from the last 32 samples of the symbol. On the other hand, both the narrow band OFDM signals are formed with 64 point transform. Each of the symbols consists 24 occupied frequency bins and first narrow band modulator bins are modulated by QPSK and other modulator bins are modulated by 16QAM. All modulators have OFDM packet consisting 50 OFDM symbols and cyclic prefix is taken from the last 16 samples of the symbol. Figure 4.52 shows time series and spectrum of the wide band and QPSK modulated narrow band OFDM signal.

Figure 4.52. OFDM modulation time series and spectrum for the wide band and QPSK modulated narrow band signal.

Figure 4.53 represent a scenario where channelizer is implemented at the cell site and two narrow band and a wide band OFDM channels are communicating in the LTE uplink and downlink system.
Figure 4.53. LTE downlink system with a wide band and two narrow band OFDM channels.

Figure 4.54. LTE uplink system with a wide band and two narrow band OFDM channels.

Say in the LTE downlink system, three users UE1, UE2, and UE3 are transmitting two narrow band and a wide band OFDM packet to three other users UE5, UE6, and UE7 respectively who are under the same cell coverage. The communication up to the cell site is through backhaul fiber or microwave links. The two narrow band signals are directly delivered to the 32-path synthesizer but the wide band signal is disassembled into 3 segments by a 4-to-2 down sampler analysis channelizer. Then these three fragments are delivered to the synthesizer with its expected sample rate and bandwidth. The 2-to-32 up-sampler synthesis channelizer performs up-sampling of the input signals and their frequency bands translated from base band to the selected center frequency by the channelizing process. A
handshake can take place between the base station and the recipients that informs the receiver to extract its center frequency of interest.

Our main concern is the LTE uplink system when the users located in different distances from the base station start transmitting back. In the uplink system, 32-to-2 down converter channelizer is implemented where the input composite signal have been down sampled and their frequency bands have been translated to base-band by the aliasing channelizing process. To recombine the segments of the wide band signal, all the wide band signal fragments are delivered to a 2-to-4 synthesis channelizer where the input time series are up-sampled and translated to their proper spectral region.

To demonstrate the channelizer performance with both narrow and wide band signals in the LTE uplink system, first we assume that all the narrow band OFDM channels from transmitter 5, 6 and 7 arrive at the base station at the same time without any frequency offset and channel gains.

The signals are added together in the free space and delivered at the input of the 32-to-2 down sampler analysis channelizer. For our simulation purpose a 32 path synthesis channelizer is used which forms a composite signal translating base band frequencies to the selected center frequencies. The wide band signal from transmitter 7 is delivered to a 4 path analysis channelizer.

Figure 4.56 presents the time and frequency response of the output time series of all the 4 channels from the 4-path analysis channelizer.
It is observed that the wide band signal is decomposed into three segments that match the expected clock rate of the next channelizer. Then these segments are delivered to the 2-to-32 up converter synthesizer and reassembled into the wider bandwidth super channel as seen in Figure 4.57.

The two other narrow band signals are also delivered to the input of the 32 path synthesizer and it performs up-sampling of the input signals and their frequency bands translated from base band to the selected center frequency by the channelizing process.
Figure 4.58. Composite signal time series and spectrum.

The composite signal is delivered to a 32 path analyzer channelizer which has partitioned their bandwidths into several fragments and aliased every segment to baseband.

Figure 4.59. 32-to-2 Down Converter Analysis Channelizer output time series (15 channels).
Figure 4.60. 32-to-2 Down Converter Analysis Channelizer output spectra (15 channels).

Figure 4.59 and 4.60 show the time and frequency response from the 15 channels of the polyphase 32-to-2 analysis channelizer engine. The down converter polyphase channelizer has partitioned the entire spanned frequency range into 32 segments.

From Figure 4.60 it’s easy to recognize the different spectra composing the received signal. Bin14 (Channel#-3) and Bin22 (Channel#5) are occupied by the two narrow band OFDM signals and the wide band signal occupies three bins(16,17 &18) from the channelizer channels. The wide band signal segments from the 32 path analyzer output are delivered to a 2-to-4 synthesizer input. This synthesizer has performed up sampling and translated and reassembled previously fragmented spectral segments and reconstructed the wide band signal.

Figure 4.61 represents the real and imaginary part of the assembled signal time series and the corresponding spectrum at the output of the 4 path synthesis channelizer.
Figure 4.61. Output time series from 4-path Synthesizer and assembled signal spectrum.

Demodulated narrow band signals taken from bin 18 and 22 of the 32 path channelizer output and the demodulated wide band signal from the 4 path synthesizer output are presented in Figure 4.62 & 4.63 respectively.

Figure 4.62. Real part and the signal constellation for the demodulated narrow band OFDM signals.
Here it is observed that the signal constellations shrink to one point and the narrow and wide band OFDM signals are perfectly demodulated maintaining their orthogonality. It proves that when all the signals arrive at the cell site at the same time in the LTE uplink system, the channelizer demonstrates the correct functionality in demodulating the narrow band as well as wide band OFDM channel without any distortion and preserving the orthogonality.

The main challenge is when the signals arrive at the cell site at different time. Figure 4.64 shows the scenario when the two narrow band and a wide band OFDM channels are coming at the base station at different time. For the simulation purpose we assume there’s no channel distortion or frequency offset to the OFDM signals.
From the OFDM modulation time series we can see that signal from the transmitter-6 arrives at the cell site with 15 samples delay and the wide band signal from transmitter-7 experiences longer (50 samples) delay.

Figure 4.65. OFDM modulation time series with timing delay in the signals from transmitter 6 and 7.

From Figure 4.66 we can see the demodulated time delayed signals where the narrow band signals are taken from the 32 path analyzer output bins and the wide band signal is captured from the 4 path synthesizer output.

Figure 4.66. Demodulated narrow band and wide band OFDM signals that arrive at the cell site at different times.
Because of the timing delay the demodulated narrow band signal from transmitter 6 (QPSK modulated) and the wide band signal show significant degradation in the samples. On the other hand the receiver is able to demodulate the narrow band (16QAM modulated) signal from transmitter 5 without any distortion in the samples and orthogonality is also preserved.

Preambles can be formed to estimate and correct the timing offsets. To check the correct functionality of the channelizer, known delays have been used in demodulation without going through the acquisition process. 15 and 50 samples timing offsets have been used during the demodulation process for the time delayed narrow band and wide band signal respectively and Figure 4.67 represents both the demodulated signal after timing offset correction.

This shows that both the time delayed narrow and wide band signals can be demodulated perfectly estimating the correct timing offset.

![Demodulated Narrow band OFDM Signal (QPSK)](image1)

![Demodulated Wide band OFDM Signal](image2)

**Figure 4.67.** Real part and the signal constellation for the demodulated time delayed narrow and wide band OFDM signal after correcting timing offset.

Similarly the channelizer is also capable of demodulating both narrow and wide band signals having frequency offsets as shown in Figure 4.68.

Each channel of the channelizer is independent of each other and the occupied signals in different channelizer channels can be demodulated separately without affecting other channels. The above discussion proves that even though the narrow or wide band signals
arrive at the cell site with timing or frequency offset or different channel gains, they can be demodulated independently from different channelizer bins without breaking the orthogonality.

Figure 4.68. Demodulated narrow band and wide band OFDM signals with frequency offset and after correction.
CHAPTER 5

CONCLUSION

5.1 SUMMARY OF THE THESIS

In this thesis we have investigated channelizer performance to synchronize uncoordinated future LTE uplink system. Chapter 2 provides the general overview of the LTE architecture and physical layer. Chapter 3 describes the current coordination process in the standard LTE uplink system and also examines the effects in case of coordination failures in future systems. In chapter 4 we have discussed implementation and performance of polyphase channelizer to demodulate both narrow and wide band signals in the LTE uplink system. Instead of using standard M-path design we have used M-to-2 down converter channelizer in this study which prevents aliasing at the neighboring channels band edge. This study proves that implementing polyphase channelizer at the base station provides more efficient way of synchronization eliminating the need of time alignment procedure. Each channel of the channelizer is independent of each other and the occupied signals in different channelizer channels can be demodulated separately without affecting other channels. We have investigated channelizer performance to demodulate both narrow and wide band signals in the LTE uplink system and it is demonstrated that even though the narrow or wide band OFDM signals arrive at the cell site with timing or frequency offset or different channel gains, they can be demodulated independently from different channelizer bins without breaking the orthogonality. This demonstrates versatility of the channelizer in synchronizing signals in LTE uplink system.

5.2 FUTURE WORKS

In this thesis we have investigated channelizer performance using orthogonal frequency division multiplexing signals. Further investigation can be done using single carrier OFDM signals which provide better peak to average power ratio in the LTE uplink system. Spectral shaping can be applied to the single carrier OFDM signals. Channelizer
performance can also be investigated with potential multicarrier techniques for the next generation wireless communication systems.
REFERENCES


