Channel Characterization for LTE

A thesis presented
by

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Abstract

In this report, channel characterization for LTE is investigated through the stages of synchronization, demodulation, channel estimation and data analysis. For the beginning of the research, a series of LTE signals from commercial LTE base stations were recorded with one receiving antenna using software radio. The synchronization of these signals is accomplished using cyclic prefixes in locating the start of an arbitrary OFDM symbol (as the start of demodulation) and primary synchronization signals for frame timing. Then, due to the position arrangement in time-frequency resource grid, secondary synchronization signals can be acquired directly afterwards. Together with the knowledge of both synchronization signals and information thereby derived, the transmitted reference signals can be generated in the receiver and the received reference signal can be retrieved from recorded LTE signals. Thus, channel estimation can be performed utilizing both generated and received reference signals. Finally, the characterization of the channel can be conducted based on the result of channel estimation.

Contents

Chapter 1

Introduction and Summary

1.1 Structure of the Report

This report consists of the following parts:

- Introduction of the area, the purpose, aim, methodology employed and limitations of this report (Chapter 1);
- Study of LTE frame structure type 1, LTE downlink slot structure, LTE physical signals as well as the signal model used in this report (Chapter 2);
- Discussion about applied receiving methods and channel estimation methods (Chapter 3).

1.2 Introduction to the Area

1.2.1 Conception of LTE

The conception of LTE can be traced back to TSG-RAN meeting #25 in early September 2004 at Palm Springs, CA, USA, during which a workshop named '3GPP TSG RAN Future Evolution Work Shop' was announced. In this workshop which took place in the beginning of November 2004 in Toronto, Canada, NTT DOCOMO proposed a concept called 'Super 3G', which later obtained support from 26 companies and effected 'Proposed Study Item on Evolved UTRA and UTRAN' at TSG-RAN meeting #26 in December 2004 in Athens, Greece. The proposals were approved in the same month. Thus began the life cycle of LTE.

Despite of the then enhancements like HSDPA and Enhanced Uplink, the justification of the proposals at TSG-RAN meeting #26 was argued that in order to secure competitiveness in a ten-year or even longer time frame from then on, it was necessary to consider a 'long-term evolution' of the 3GPP radio access technology, which should mainly encompass reduced latency, higher user data rates, improved system capacity and coverage, and reduced cost for the operators.

In year 2007, Evolved UTRA was established as the first issue of approved Technical Specifications. As these specifications became stabilized, they were frozen later in December 2008 and have been the basis for the first wave of LTE apparatus. The enabling technologies for Evolved UTRA includes OFDM, OFDMA, Single Carrier Frequency Division Multiple Access (SC-FDMA), MIMO and etc.

Now both radio and core network evolution part of LTE are on the market, which generates room for studies on commercial LTE networks, as manifested by this report which is based on signals recorded from LTE FDD downlink transmission.

1.2.2 Overview of the Downlink of LTE System

Since this report is based on the downlink of LTE system, it is beneficial to briefly overview its content before going into more specific detail. Downlink here refers to the traffic and its corresponding conduits from eNodeBs to UEs, which include downlink physical channels, downlink physical signals and available modulation schemes for data channel, as listed below.

The donwlink physical channels consist of:

- Physical Broadcast Channel (PBCH);
- Physical Control Format Indicator Channel (PCFICH);
- Physical Downlink Control Channel (PDCCH);
- Physical Hybrid ARQ Indicator Channel (PHICH);
- Physical Downlink Shared Channel (PDSCH);
- Physical Multicast Channel (PMCH).

The donwlink physical signals consist of:

- Reference signal;
- Synchronization signal.

Finally, available modulation schemes for the data channel are:

- QPSK;
- 16-QAM;
- 64-QAM.

1.2.3 Measurement and Processing Setup

The measurement of the LTE signals is done by using software radio, a modulerized system necessary components for data acquisition, which runs an LTE-compatible recording program written in LabView from National Instruments. The machine which runs the software radio can also run MATLAB scripts which process the recorded data and produce the desired results, i.e. channel estimation.

1.2.4 The Issue of Synchronization

As decribed above, there was only simplex communication involved during the measurement. Hence, the synchronization of the recorded LTE signals could be potentially challenging. Under this circumstance, the following scheme is employed to synchronize the recorded data. First, locate the beginning of an arbitrary OFDM symbol using the property of high auto-correlation of the cyclic prefix. This is referred to as coarse timing in this report. Second, find the start of an arbitrary primary synchronization signal (PSS) using the OFDM symbol-based timing information and the property of the Zadoff-Chu sequence present in the PSS. Finally, with correctly decoded PSS, secondary synchronization signals (SSS) can be retrieved from the recorded data with good accuracy in timing, which in turn can help determine the beginning of a frame using the knowledge of SSS generation. This is called frame timing in thie report.

1.3 Purpose of the Report

The purpose of this report is to evaluate the feasibility of the idea of devising a channel charaterization system for commercial LTE eNodeBs working in FDD mode using accessible resources within the Department of Electrical and Information Technology at Lund University, i.e. a modularized software radio system from National Instrusments set up for data acquisition, a monopole antenna which functions within the frequency band of LTE downlink transmission, power supply for the measurement systems and etc.

1.4 Aim

The establishment of a fully functioning system which is capable of executing channel estimation using signals transmitted from commercial LTE eNodeBs working in FDD mode.

1.5 Methodology

1.5.1 Feasibility Study

In the beginning of this project, a study was conducted on several 3GPP specifications regarding LTE physical layer in order to establish a viable scheme to assure successful and reliable channel estimation for LTE.

1.5.2 Benchmarking

After a scheme became recognized as a candidate for the channel estimation system, it was validated through simulation and testing with recorded LTE signals. The candidate which provides the highest accurary was elected.

1.5.3 Implementation and Refinement

Following the benchmarking, there is a full implementation of the system, which includes debugging, profiling, other relevant refinement and etc.

1.5.4 Summary

This report was generated to summarize the essential and presentable work within the scope of this project.

1.6 Limitations

- Only LTE in FDD mode is considered within the scope of this report, due to limited access to LTE systems;
- Only static (every element of the channel stay constant) or quasi-static channels (some elements of channel changes slightly over a long period of time comparing to the recording time duration) are compatible input for implemented channel estimation system, because of conceived estimation method;
- 20MHz LTE systems are not well supported as a result of the sampling rates provided by the deployed software radio.

Chapter 2

LTE Physical Layer, Physical Signals and Signal Model

Due to limited access to commercial LTE systems, only LTE operating in FDD mode is considered. Additionally, as decribed previously, only simplex communication took place during the project. Therefore, only the downlink part of LTE is of concern and discussed here.

2.1 LTE System And LTE Physical Layer

2.1.1 LTE Protocol Architecture

Figure 2.1 demonstrates the position of the focus, physical layer, of this report within the architecture of LTE protocols.

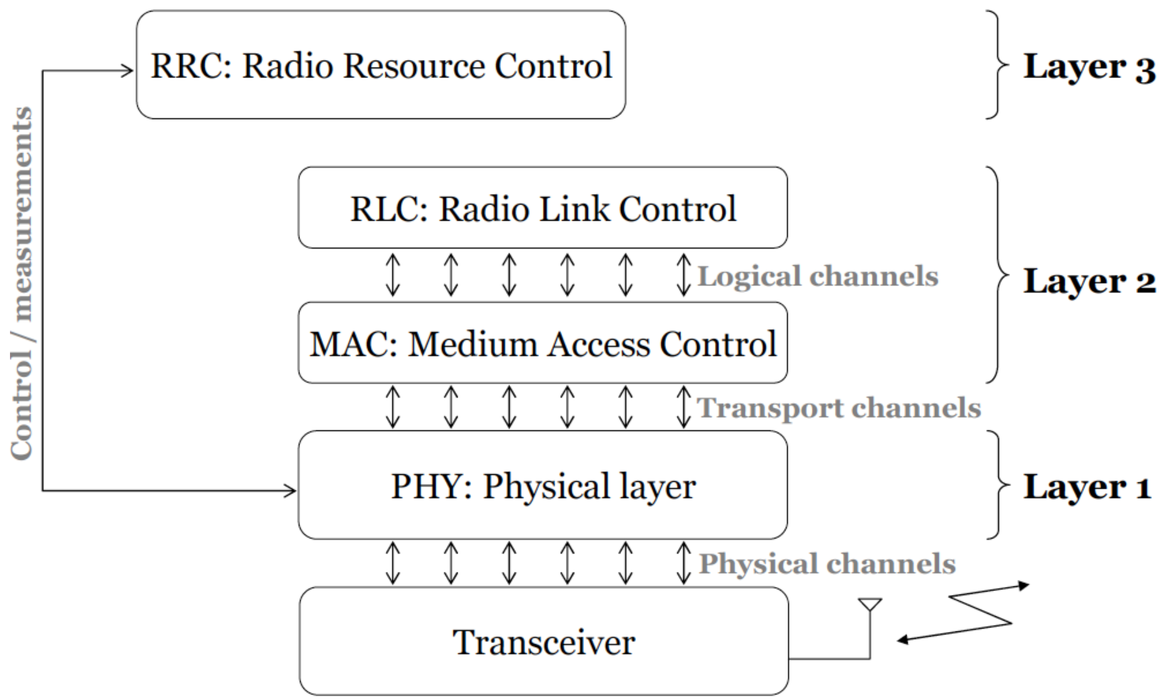

Figure 2.1: LTE Protocol Architecure [1]

2.1.2 The Scope of LTE Physical Layer

The downlink part of the LTE physical layer consists of the following areas[2]:

- Modulation Parameters
- Downlink Multiplexing
- Physical Channels
- Physical Signals
- Transport Channels
- Mapping Downlink Physical Channels to Transport Channels

2.1.3 LTE Frame Structure

There are two radio sturctures defined for LTE, frame structure type 1 (FS1) for FDD LTE and frame strcture type 2 (FS2) for TDD LTE. Due to the scope of this report, only FS1 is considered here. As illustrated in Figure 2.2, one LTE radio frame has the length of $T_{frame} = 10ms$. In every LTE radio frame, there are ten subframes with the same length, which is $T_{subframe} = 1ms$.

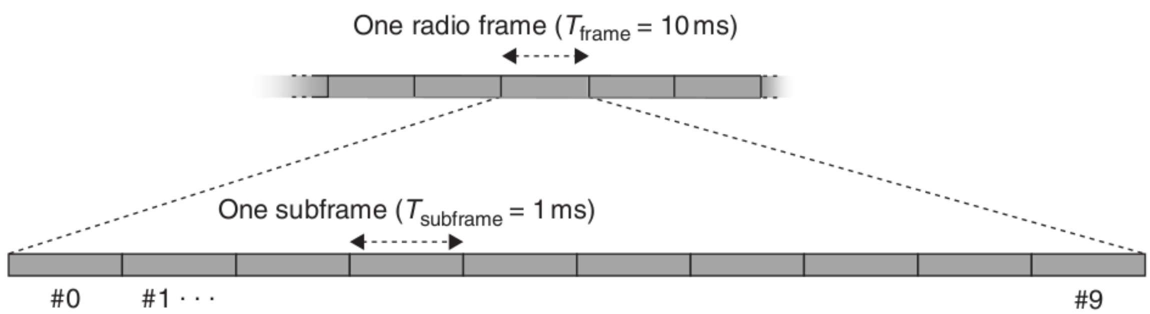

Figure 2.2: LTE Frame Structure [3]

Each subframe in the LTE frame structure can be further split into two slots equal in length, which is $T_{slot} = 0.5ms$. Within each slot, there are several OFDM symbols and cyclic prefixes. The slots in one LTE radio frame are numbered from 0 to 19.

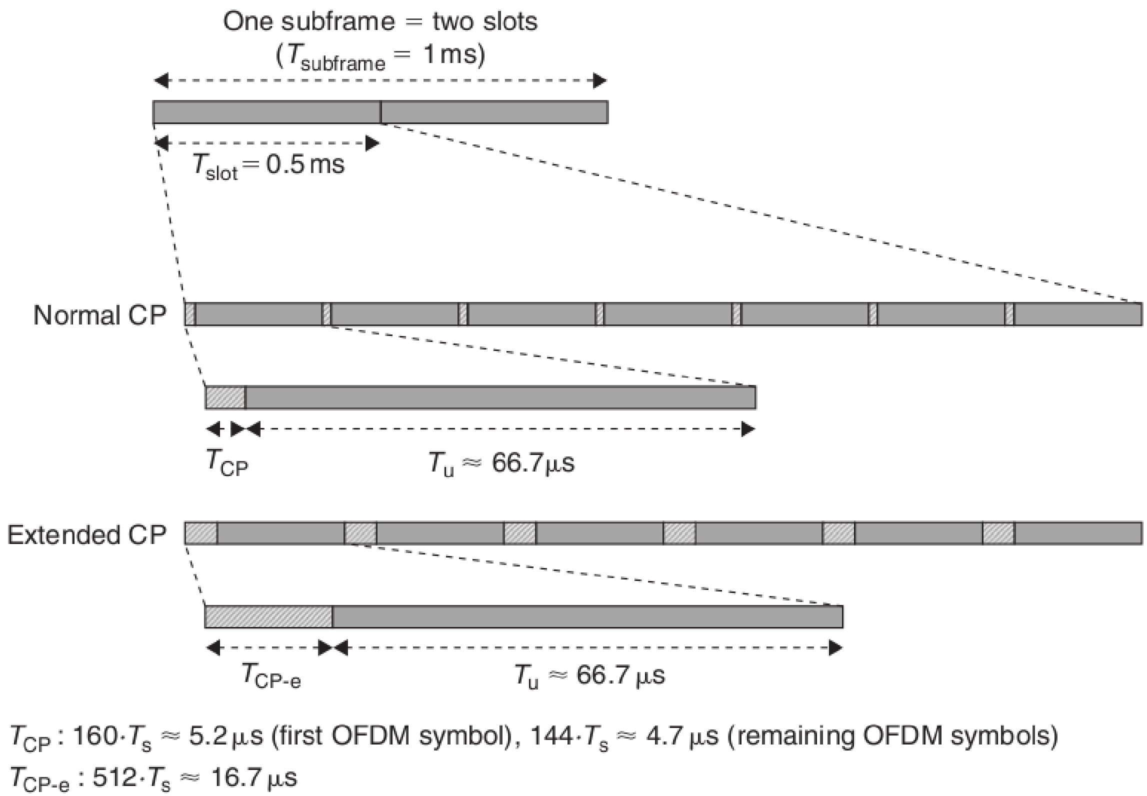

Figure 2.3: Detailed LTE Frame Structure [3]

2.1.4 LTE Downlink Resource Grid

According to the 3GPP specifications, LTE downlink transmission utilizes Orthogonal Frequency Division Multiplex (OFDM). Hence, the basic physical resource employed in LTE downlink can be viewed as a time-frequency resource grid, which consists of many resource elements, which in turn represent certain OFDM subcarriers during certain single OFDM symbol time. The OFDM subcarrier spacing in LTE downlink is specified to be $\Delta f = 15kHz$.

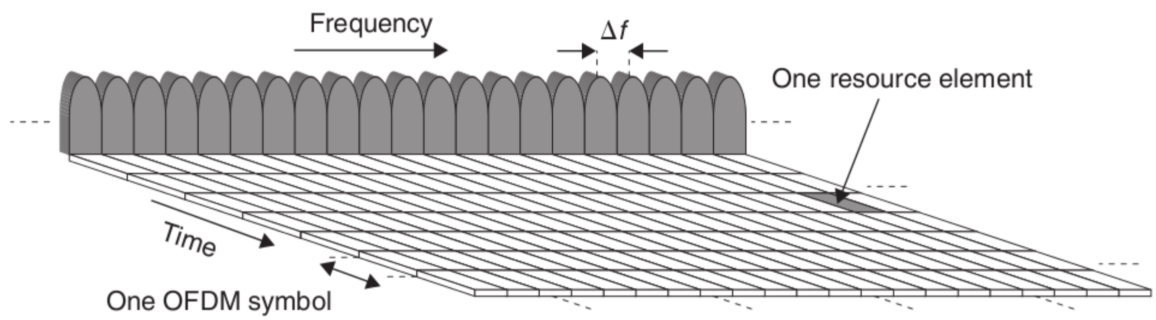

Figure 2.4: LTE Downlink Physical Resource. Figure from [3]

In LTE downlink transmission, the mapping of certain physical channels to resource elements is described, using resource blocks. As far as this thesis is concerned, it is only necessary to investigate physical resource block, which is defined as a block of $N_{symb}^{DL} \times N_{sc}^{RB}$ resource elements, where N_{symb}^{DL} denotes the number of OFDM symbols in a downlink slot and N_{sc}^{RB} denotes the number of subcarriers in a resource block.

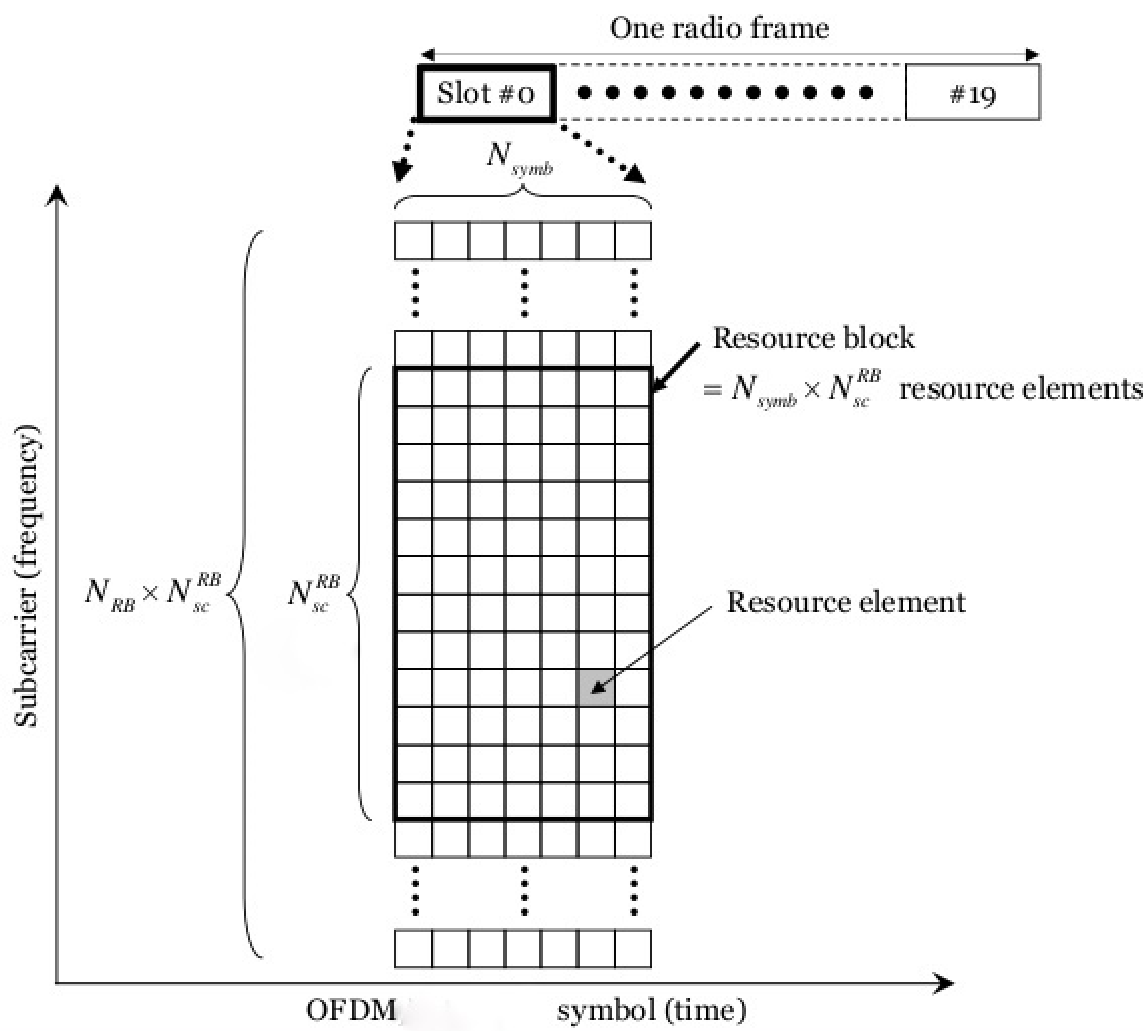

Figure 2.5: LTE Downlink Resource Grid. Figure from [4]

2.2 Physical Signals

A series of resource elements employed by the physical layer but carries no information orginated from high layers are referred to physical signals, which are defined into two categories:

- Reference Signal

- Synchronization Signal

2.2.1 Reference Signals

Purpose

Known symbols are inserted into LTE resource grid to enable channel estimation. Several kinds of combination of these symbols are specified as reference signals. For LTE downlink transmission, there are three types of reference signals defined:

- Cell-specific reference signals
- MBSFN reference signals
- UE-specific reference signals

MBSFN reference signals are used in MBSFN transmission, namely Multicast Broadcast Single Frequency Network transmission, which incorporates more than one cell to utilize the same reference signal at the same time. This results in receiving a combined reference signal at the LTE signal recording device for channel charaterization, which cannot be used for channel estimation for a single cell. Given MBSFN mode utilizing extended cyclic prefix only, if always assume only normal cyclic prefix is present when processing recorded signal, MBSFN reference signals can be avoided for channel charaterization.

In normal cyclic prefix scenario, cell-specific reference signals and UE-specific reference signals make no difference to the scheme of acquiring reference signal, which is to be elaborated in the third part of this chapter. Hence these two kinds of reference signals are both candidates of research objects in this thesis.

Sequence Generation

All three kinds of reference-signal sequences are defined in a single form:

$$RS_{iOFDM,islot}(m) = \frac{1}{\sqrt{2}}(1 - 2 \cdot c(2m)) + j\frac{1}{\sqrt{2}}(1 - 2 \cdot c(2m+1)), \qquad (2.1)$$

where $iOFDM$ represents the OFDM symbol number within a slot, $islot$ denotes the slot number within an LTE radio frame and $c(i)$ is pseudo-random sequence defined for various application in LTE. The differences between these three kinds of reference-signal sequence are sequence length and different initial states for the pseudo-random sequence in $c(i)$.

2.2.2 Synchronization Signals

The figure below shows the positions of primary synchronization signals and secondary synchronization signals within an LTE frame.

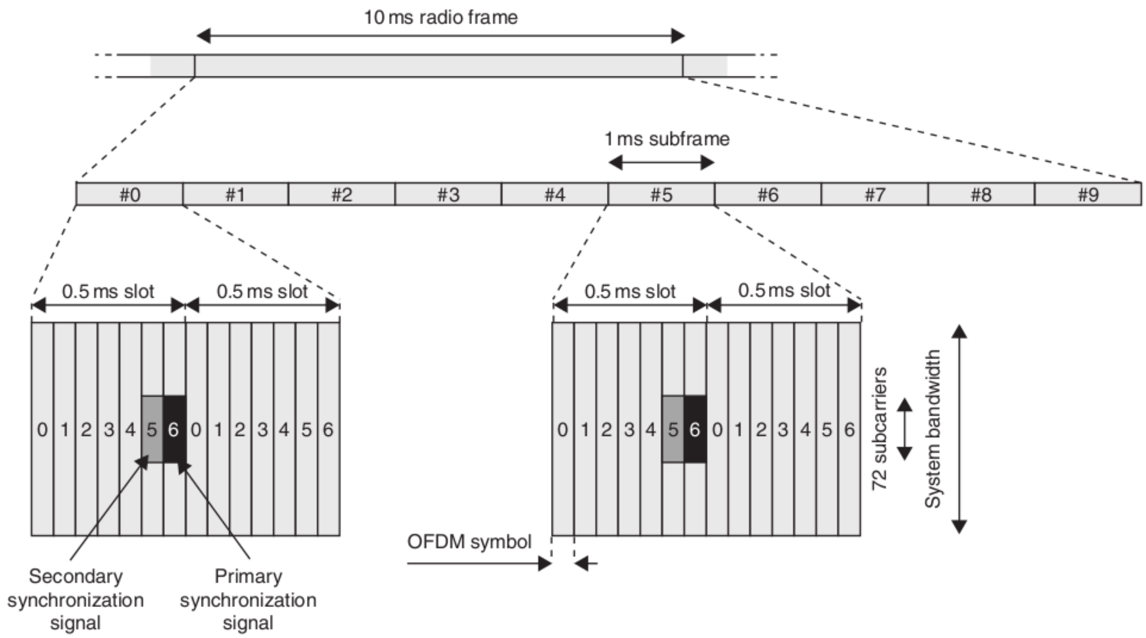

Figure 2.6: Primary and Secondary Synchronization Signals. Figure from [3]

The '72 subcarriers' refers to synchronization signals only.

Primary Synchronization Signals

Purpose

The main purposes of the primary synchronization signals in LTE downlink transmission are:

- Assisting the User Equipments (UEs) to synchroinze to downlink signals with a 0.5ms time window of inaccuracy;
- Allowing the UEs to blindly estimate the positions and length of the secondary synchronization sigals and in turn assuring relative low complexity of the reception of secondary synchronization signal;

- Passing on, to the UE, the information of the physical-layer identity within a physical-layer cell-identity group.

The physical-layer cell-identity group and physical-layer identity are introduced in subsection 2.2.3.

Sequence Generation

The sequences used for primary synchronization signals are frequency-domain Zadoff-Chu sequences defined as below:

$$ZC_r(n) = \begin{cases} e^{-j\frac{\pi r n(n+1)}{63}} & n = 0, 1, \ldots, 30 \\ e^{-j\frac{\pi r(n+1)(n+2)}{63}} & n = 31, 32, \ldots, 61, \end{cases} \tag{2.2}$$

where r denotes the Zadoff-Chu root sequence index and n is the numbering of the entries of the Zadoff-Chu sequences.

Secondary Synchronization Signals

Purpose

The functionality that secondary synchronization signals can provide is:

- Frame timming, namely fine synchroinzation within the range of a slot;
- Delivering the information of physical-layer cell-identity group.

Sequence Generation

The sequence used for secondary synchronization signal is defined as below:

$$SS(2n) = \begin{cases} s_0^{(m_0)}(n)c_0(n) & \text{in subframe 0} \\ s_1^{(m_1)}(n)c_0(n) & \text{in subframe 5} \end{cases} \tag{2.3}$$

$$SS(2n+1) = \begin{cases} s_1^{(m_1)}(n)c_1(n)z_1^{(m_0)}(n) & \text{in subframe 0} \\ s_0^{(m_0)}(n)c_1(n)z_1^{(m_1)}(n) & \text{in subframe 5} \end{cases} \tag{2.4}$$

where $0 \leq n \leq 30$, $s_1^{(m_1)}(n), s_0^{(m_0)}(n), c_0(n), c_1(n), z_1^{(m_0)}(n)$ and $z_1^{(m_1)}(n)$ are m-sequences that bear different information which is to be explained further in next section.

2.2.3 Relations Among Physical Signals

In LTE, there are 504 different physical-layer cell identities (N_{ID}^{cell}), which are categorized into 168 physical-layer cell-identity groups ($N_{ID}^{(1)}$), each of which consists of 3 identities ($N_{ID}^{(2)}$). Thus,

$$N_{ID}^{cell} = 3N_{ID}^{(1)} + N_{ID}^{(2)}. \tag{2.5}$$

The reference signals in LTE is the bearer of physical-layer cell identities (N_{ID}^{cell}) which are incorporated into different types of reference signals by the pseudo-random sequences $c(i)$ whose initial states are defined with N_{ID}^{cell}.

The primary synchronization signals carries the information of physical-layer identity within a physical-layer cell-identity group, $N_{ID}^{(2)}$, which is expressed by root indices in the definition of sequence generation for primary synchronization.

$N_{ID}^{(2)}$	Root Index
0	25
1	29
2	34

Table 2.1: Root Indices for the Primary Synchronization Signal

The secondary synchronization signal contains information about the physical-layer cell-identity group in $s_1^{(m_1)}(n), s_0^{(m_0)}(n), z_1^{(m_0)}(n)$ and $z_1^{(m_1)}(n)$, and the information about the physical-layer identity in $c_0(n), c_1(n)$.

Therefore, with the proper reception of the synchronization signals, the reference signal can be generated with the knowledge of $N_{ID}^{(1)}$ and $N_{ID}^{(2)}$.

2.3 Signal Model

Let θ denote the delay between the time instances of the start of the recorded data and the start of the signals of interest. Additionally, let ε denote the frequency difference between the oscillator in the transmitter and the oscillator in the receiver. Then the received the signals among the recorded data can be expressed in the following way:

$$r(k) = s(k-\theta)e^{j2\pi\varepsilon k/N} + n(k), \tag{2.6}$$

where $s(k)$ denotes the transmitted time-continuous signal, N stands for the number of sub-carriers, and n denotes additive white Gaussian noise (AWGN). Since the attenuation of the received signals is not of interest here, it is set to 1 for the sake of clarity. According to 3GPP specification 3GPP TS 36.211 Rel-8 8.9.0, $s(t)$ within an arbitrary OFDM symbol in a LTE downlink slot is defined by

$$s(t) = \sum_{l=-\lfloor N_{RB}^{DL} N_{SC}^{RB}/2 \rfloor}^{-1} a_{l^{(-)}} \cdot e^{j2\pi l \Delta f (t - N_{CP} T_S)} + \sum_{l=1}^{\lceil N_{RB}^{DL} N_{SC}^{RB}/2 \rceil} a_{l^{(+)}} \cdot e^{j2\pi l \Delta f (t - N_{CP} T_S)} \quad (2.7)$$

for $0 \leq t < (N_{CP} + N_{DFT} \times T_S)$, where $l^{(-)} = l + \lfloor N_{RB}^{DL} N_{SC}^{RB}/2 \rfloor$,$l^{(+)} = l + \lfloor N_{RB}^{DL} N_{SC}^{RB}/2 \rfloor - 1$, a_l denotes the value of a certain resource element, N_{RB}^{DL} denotes the number of resource block used in downlink, N_{DFT} denotes the size of DFT, which is also the length (in the unit of number of samples) of the part of an OFDM symbol that bears information.

Assuming that a_l are independent from each other, yet possess the same random distribution; and N_{DFT} is large enough ($N_{DFT} = 1024$ in recorded LTE signals). Then, according to central limit theorem, $s(k)$ approximates a complex Gaussian process, since it is a linear combination of independent random variables with identical distribution. Accordingly, received signal $r(k)$ approximates a complex Gaussian process, too. This property of $r(k)$ is the foundation of reasoning for the optimization method used for θ and ε in coarse timing.

Chapter 3

Charaterization for LTE with One Receiving Chain

In this chapter, a detailed discription of the entire process of channel characterization for LTE with one receiving chain is presented, which encompasses coarse timing synchronization, frame timing synchronization, carrier frequency offset compensation, synchronization signals reception, reference signals reception and channel estimation, as illustrated in the following flow chart.

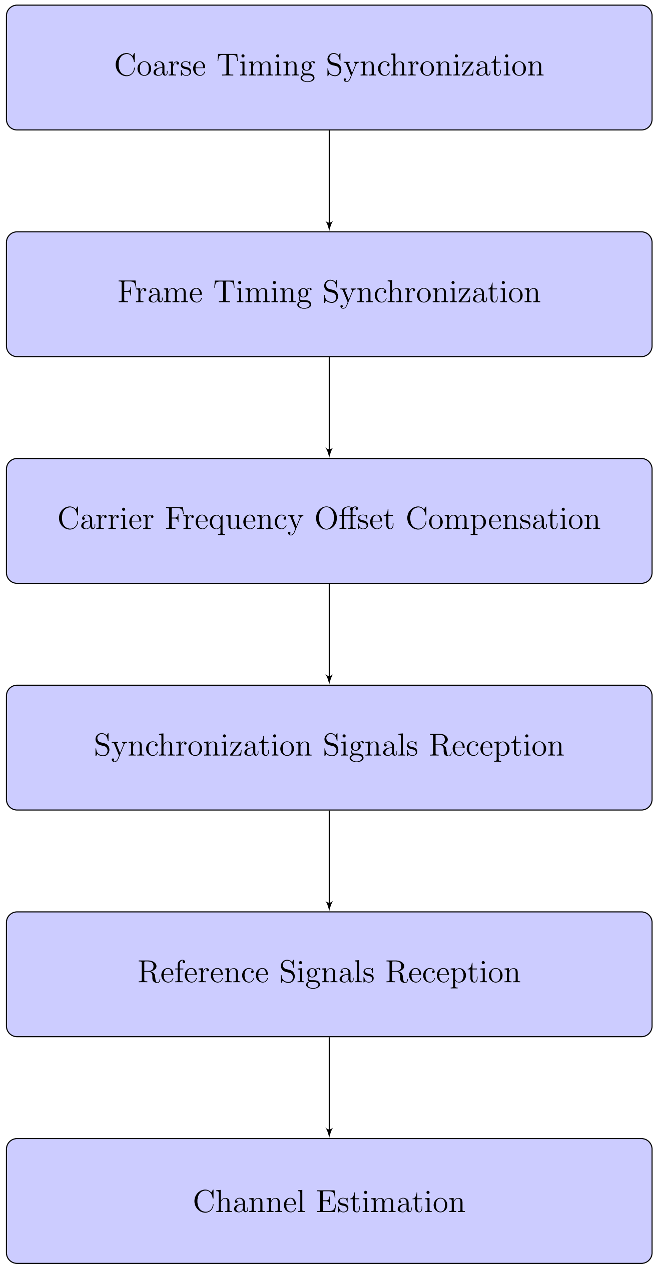

Figure 3.1: Processing Flow

3.1 Coarse Timing Synchronization

The objective of the coarse timing synchronization is to locate an arbitrary (one OFDM symbol within the duration of one LTE radio slot starting form the beginning of the reorded data, for the ease of signal processing) OFDM symbol inside the recorded LTE signal. The goal of this step of reception is to find the timing offset (represented as θ in this report) for the beginning of the first detectable OFDM symbol with the employed coarse timing synchronization method.

3.1.1 Algorithm

This paper employs joint maximum likelihood (ML) symbol time and carrier frequency estimator in OFDM systems[5] in coarse timing synchronization. The reason for this choice is its reliability and functionality in the initial search for OFDM symbol start as well as carrier frequency offset computation. The estimator (marked as $\Lambda(\theta, \varepsilon)$) applied can be expressed as below

$$\Lambda(\theta, \varepsilon) = |\gamma(\theta)| \cos(2\pi\varepsilon + arg(\gamma(\theta))) - \rho\Phi(\theta), \tag{3.1}$$

where

$$\gamma(\theta) \equiv \sum_{k=\theta}^{\theta+L-1} r(k) r^*(k + N_{DFT}), \tag{3.2}$$

$$\Phi(\theta) \equiv \frac{1}{2} \sum_{k=\theta}^{\theta+L-1} [|r(k)|^2 + |r(k + N_{DFT})|^2], \tag{3.3}$$

$$\rho \equiv \left| \frac{E\{r(k)r^*(k+N_{DFT})\}}{\sqrt{E\{|r(k)|^2\}E\{|r(k+N_{DFT})|^2\}}} \right|, \tag{3.4}$$

where L is defined here as the length of normal cyclic prefix N_{CP2} in LTE specifications. By maxmizing the estimator function, a θ which marks the start of an OFDM symbol in the recorded data can be found.

If the input of the estimator, $r(n)$, is as shown in Figure 3.2, which in this case is one LTE radio slot (1/20 of one LTE radio frame) represented by samples recorded from a commercial LTE eNode B with a $25MHz$ sample rate, where there are two OFDM symbols, reference signals to be accurate, with dominant magnitude and the rest of the OFDM symbols bearing no user information or primary/secondary synchronication signals.

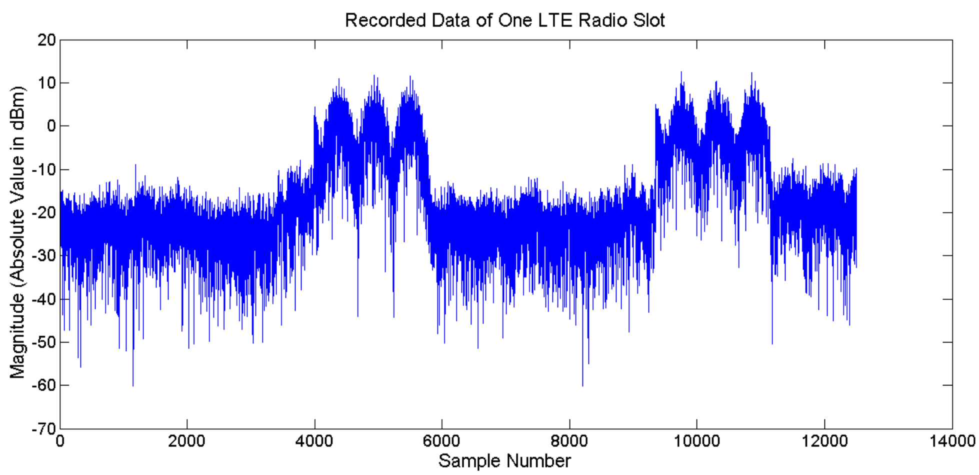

Figure 3.2: Recorded Data of One LTE Slot

The value of the Λ function calculated from this input signal can be shown as in Figure 3.3. It can be observed from the two previous figures that, for the data recorded from the commercial base transceiver stations, the vertices with the two highest values in Figure 3.3 occur at the same spots where the cyclic prefixes of the two OFDM symbols start. Hence, the employed estimator Λ function can indeed

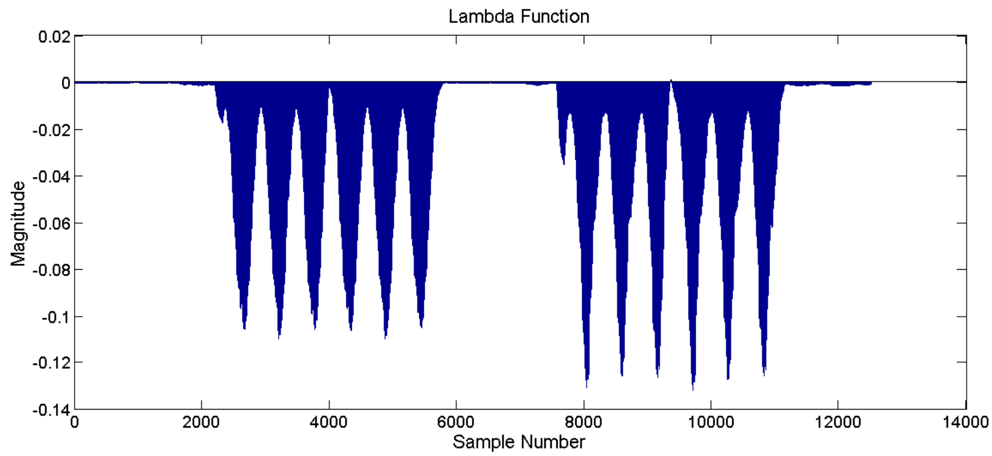

Figure 3.3: Λ Function Used for Coarse Timing Synchronization

perform the functionality of coarse timing synchronization with accuracy.

3.1.2 Applied Method

Range of Maximization

Due to the fact that only LTE physical signals are present in the recorded data, as shown in Figure 3.2, the maximization of the estimator is limited to the parts where LTE reference signals are the actual input. This is achieved by

1. Splitting the calculated $\gamma(\theta)$ and Λ function into segments with length of one OFDM symbol;

2. Locating the reference signals by comparing the mean value of $\gamma(\theta)$ of each segment and the mean value of $\gamma(\theta)$ of the whole input;

3. Maximizing the Λ function where the reference signals are located.

The $\gamma(\theta)$ and its mean value comparison calculated from the data shown in Figure 3.2 are shown in Figure 3.4 and Figure 3.5.

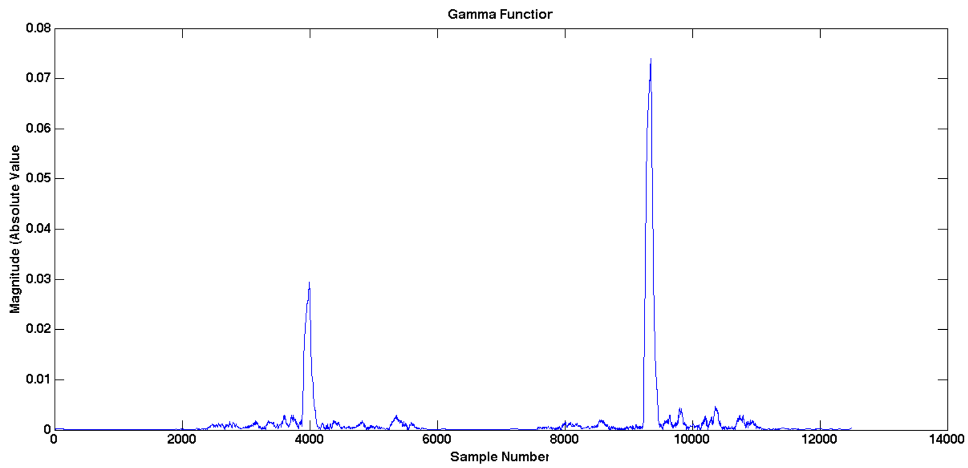

Figure 3.4: Gamma Function Used for Coarse Timing Synchronization

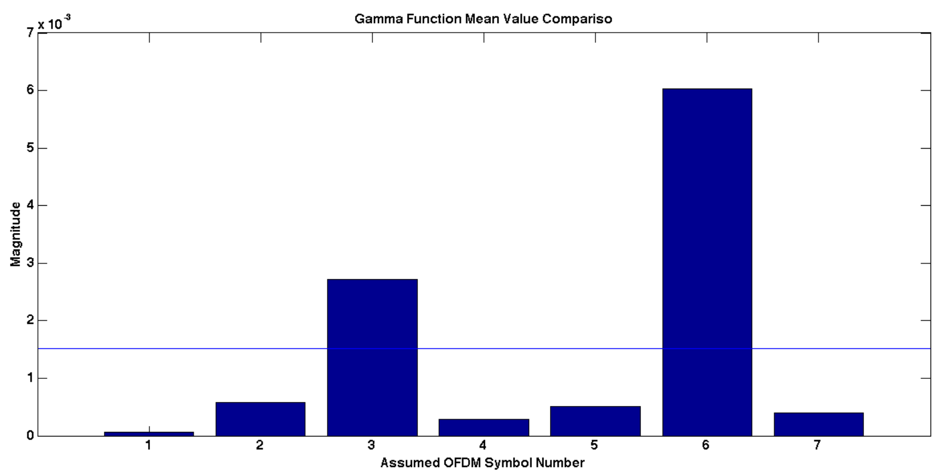

Figure 3.5: Gamma Function Mean Value Comparison

In Figure 3.5, the mean value of $\gamma(\theta)$ of the whole input of the Λ function is represented by a horizontal line to compare against the mean value of $\gamma(\theta)$ of each segment. It is obvious that the segments resulted from reference signals in the recorded data can be selected thereafter.

Calculating the Weight Factor ρ

As explained in Chapter 1, only static or quasi-static propagation channels are considered in this report, ρ, which is defined in Equation 3.4, is considered a constant value which is established using an assumed signal-to-noise ratio. The choice of the value for ρ can be arbitrary within its range. Once this value is fixed, it does not any longer affect the performance of the estimator.

3.2 Frame Timing Synchronization

As soon as the first detectable OFDM symbol of choice is recognized by the coarse timing synchronization function, it is possible to deteremine the relative position of a certain OFDM symbol within the LTE frame structure, e.g. to decide, out of the 20 slots in one LTE radio frame, which slot the one shown in Figure 3.2 is. The approach for this step of process applied in this report is exploiting the property of high auto-correlation of the sequences, Zadoff-Chu sequences, used to generate primary synchronization signals (PSS) in an LTE network.

In order to do so, a sweep search is conducted with a search step of the length of one OFDM symbol with normal cyclic prefix which is not the first OFDM symbol in a LTE slot (As per 3GPP specifications on LTE, there are normal cyclic prefixes with two different lengths used in LTE, the normal cyclic prefixes in the first OFDM symbols in LTE slots and the normal cyclic prefixes in the remaining OFDM symbols in LTE slots.), where generated PSS sequences (mapped into frequency domain) with all three root indexes are correlated with frequency domain signals conveyed by every OFDM symbol within one LTE radio frame range from the first detected OFDM symbol. The reason for choosing the length of one OFDM symobl with normal cyclic prefix located behind the first OFDM symbol in a LTE slot as the step for search by correlation is that this type of normal cyclic prefix is the obvious dominant type of cyclic prefix in the recorded data. Additionally, the reason for choosing a fixed search step is that the length difference between the two kinds of normal cyclic prefixes is relatively trivial comparing to the length of the search range. Therefore, even when timing error is introduced into this step of reception by assuming the application of a common cyclic prefix in the recorded LTE signals, the generated Zadoff-Chu sequences are correlated with the received potential Zadoff-Chu sequence in frequency domain demodulated from almost the full sequence of potential PSS. In other words, the correlation results are still valid and can be used as identifiers for received PSS. Furthermore, the reason for carrying out a sweep search for the length of an LTE radio frame is because there are two PSSs in every LTE radio frame and the disctances between adjacent PSSs are the same. This property can be exploited to help eliminate the confusion caused by secondary synchronization signals (SSS) and/or delayed version(s) of PSSs in recorded data when it comes to determining the used root index for PSS after the sweep search.

The inaccuracy of the symbol timing caused by a fixed search step is compensated later when the PSSs are located in the sweep search.

Three figures of cross-correlation maxima calculated during the sweep search are shown below for different root indices.

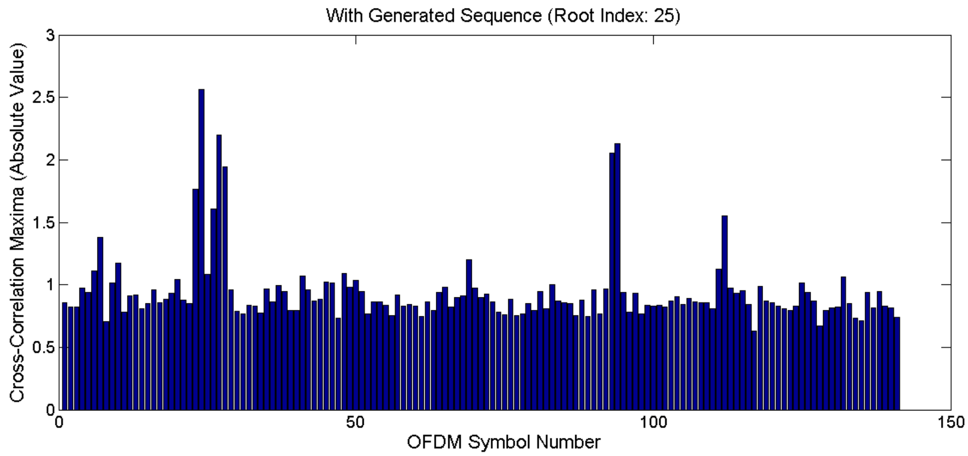

Figure 3.6: Cross-correlation with Generated Sequence with 25 as Root Index

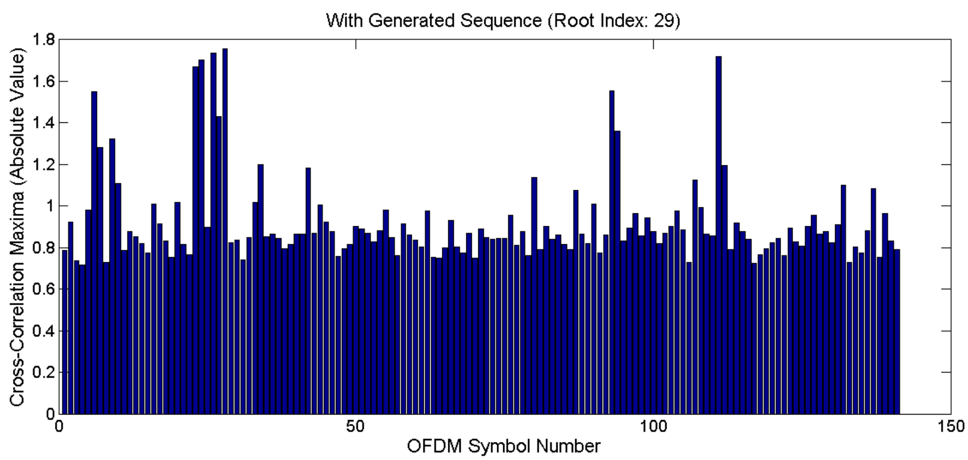

Figure 3.7: Cross-correlation with Generated Sequence with 29 as Root Index

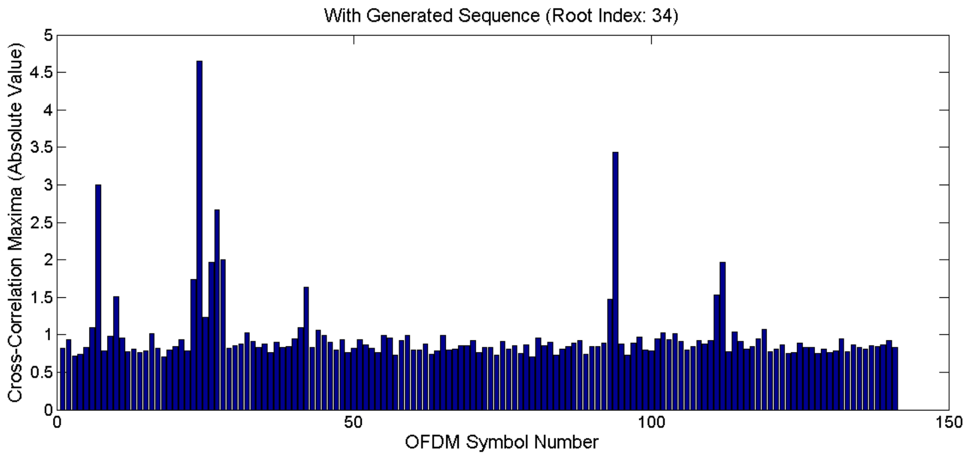

Figure 3.8: Cross-correlation with Generated Sequence with 34 as Root Index

According to the observation of previous figures, figure 3.8 shows the highest cross-correlation absolute value maxima. Consequently, for this set of recorded data that was fed to the estimator, it is most likely that PSSs with 34 as root index are recorded.

However, this maximum value of all the cross-correlation absolute values does not indicate the location of the start of the transmitted PSS (the ones without additional delays comparing to the delayed versions) in the recorded data. In order to retrieve this information, a few steps of processing need to apply to the recorded data.

1. Select a group of high cross-correlation absolute values, using an established threshold, as candidates of received PSS without additional delays;

2. Within this set of candidates, with a good selection of previously mentioned threshold, a pair of high cross-correlation absolute values can be found;

3. Adjust the position of the first PSS located in last step.

For the necessity of the position adjustment of the first received non-delayed PSS, the concept of shortest accurate length in the unit of recorded samples is discussed here. The shortest accurate length used within the scope of this report is the length of a section of the recorded data represented by the smallest integer number of recorded samples which corresponds to a defined unit in the LTE specifications which is no shorter than an OFDM symbol. Considering that the sample rate of the recorded data is $25MHz$ and the duration of one LTE radio frame is $10ms$, the shortest accurate length which can be found within the recorded data is 12500 in the unit of recorded samples, which corresponds to the length of one slot in the LTE frame structure.

Bearing this information in mind, the distance between the first located OFDM symbol with transmitted singal and the first received non-delayed PSS can be displayed in the unit of recorded samples by a combination of accurate unit length and inaccuratre unit length, the accurate unit length being the length of a slot and the inaccurate length being the remainder of this distance divided by the length of a slot. The reason for this representation is because the PSS of interest is located by using fixed-step search. Therefore, the absolute location of this PSS is the sum of the absolute location of the first located OFDM symbol conveying transmitted signal, an integer number of LTE slot and a fraction of an LTE slot. This fraction can in turn be represented by the sum of an integer number of OFDM symbols with normal cyclic prefix and a fraction of a such OFDM symbol.

The remainder of this distance mentioned above divided by the length of a slot is used to compensate the error introduced by the application of a single search step in locating PSS. And the quotient of this remainder divided by the length of an OFDM symbol with normal cyclic prefix is used to correct to error introduced by the use of aforementioned OFDM symbol length.

Thus, the accurate absolute location of the first recieved the non-delayed PSS marked in recorded samples should be obtained.

3.3 Carrier Frequency Offset Compensation

3.3.1 Fractional Carrier Frequency Offset Computation

After locating a proper θ (timing offset) for the first detectable OFDM symbol of choice in the recorded data through the maximization of the estimator function, the fractional part of estimated carrier frequency offset ε can be obtained from equation 3.1 by setting

$$\cos(2\pi\varepsilon + arg(\gamma(\theta))) = 1, \tag{3.5}$$

$$\varepsilon = \varepsilon_F + M, \tag{3.6}$$

where ε_F is the fractional part of estimated carrier frequency offset and M is an arbitrary integer number.

Given

$$|\varepsilon_F| < 1, \tag{3.7}$$

hence,

$$\varepsilon_F = -\frac{arg(\gamma(\theta))}{2\pi}. \tag{3.8}$$

3.3.2 Integer Carrier Frequency Offset Computation

According to equation 3.6, there is a possibility of integer carrier frequency offset being present in the recorded data. This integer needs to be calculated if present, to eliminate shifting in the recorded data in the frequency domain.

We employ a joint detector for integer carrier frequency offset and physical-layer cell group identities (marked by $N_{ID}^{(2)}$) proposed in [6]. This detector can be immune to symbol timing error, since it is only influenced by frequency domain channel cross-correlation. This detector only produces one peak in its output when the correct $N_{ID}^{(2)}$ is included in the detector. This property can be used to check the result of determined root index for Zadoff-Chu sequence in previously executed frame timing synchronization.

As shown in Figure 3.9, the joint detector constructed, using the frequency domain sequence of the first located PSS and determined Zadoff-Chu sequence root index, generates one peak at zero offset index.

Figure 3.9: Joint Detection Waveform For Integer CFO and $N_{ID}^{(2)}$

3.3.3 Carrier Frequency Offset Compensation

With both parts of the carrier frequency offset computed, each recorded sample within the range from the first detected OFDM symbol of choice to the end the recorded data set is compensated with a phase modifier fashioned using the results from previous two subsections.

3.4 Decoding Synchronization Signals

3.4.1 Primary Synchronization Signal

Primary synchronization signals can be located in the recorded data set with the acquired timing and then decoded using discreet Fourier transformation. This dicreet Fourier transformation is performed by multiplying received OFDM symbols with a demodulation matrix which is the pseudoinverse of the modulation matrix which can be inferred from Equation 2.7.

Figure 3.10 shows one docoded primary synchronization signal in frequency domain, where frequency resolution is marked by sub-carrier number. As one can see in this figure, the majority of the energy of this OFDM symbol lies in the central part of the spectrum, which coincides with the definition of the PSS.

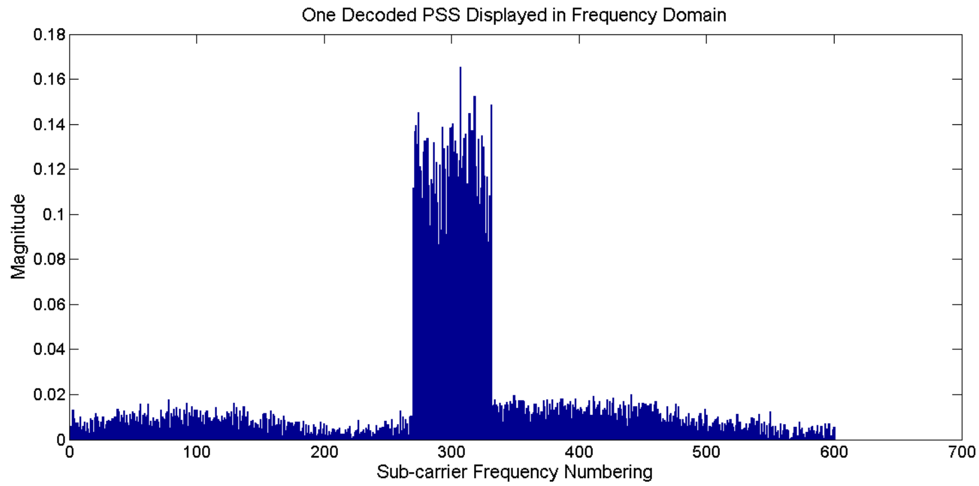

Figure 3.10: One Decoded PSS Displayed in Frequency Domain

For a fixed Zadoff-Chu sequence root index, there will be only one primary synchronization signal transmitted repeatedly. Therefore, with the knowledge of OFDM symbol timing and PSS indexes established on this OFDM symbol timing, it is quite straightforward to decode all the PSSs in the recorded data set. There is a slight improvement in the cross-correlation maxima, in terms of maxima peak absolute values, between received PSS and generated PSS, after carrier frequency offset compensation has been executed. As depicted in the following two figures, for PSS detected in frame timing synchronization as shown in Figure 3.11, the cross-correlation maxima peaks they can produce are a bit higher after carrier frequency compensation, as illustrated in Figure 3.12.

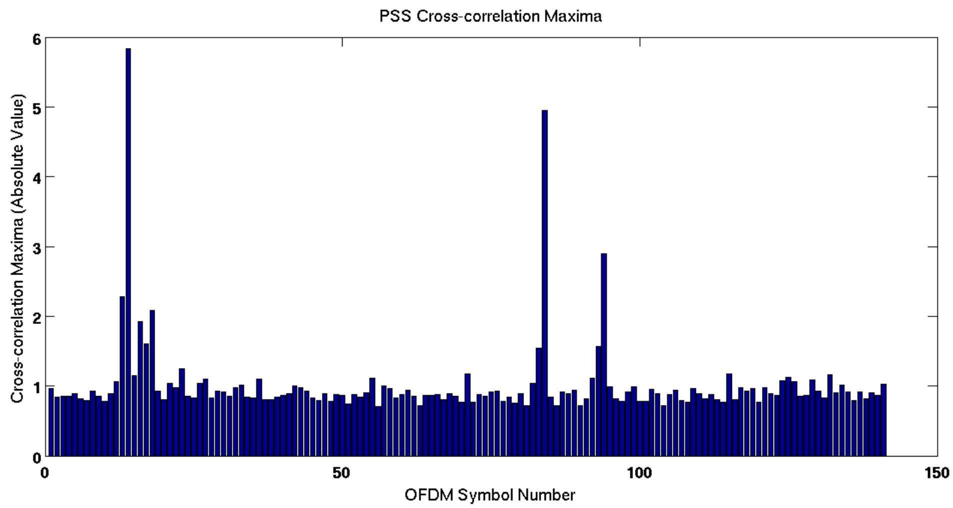

Figure 3.11: PSS Cross-correlation Maxima in One Radio Frame

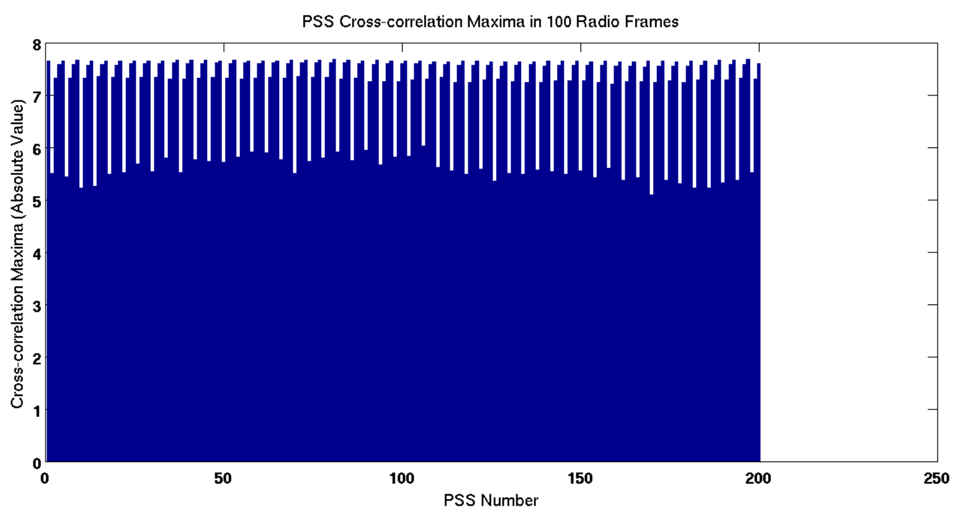

Figure 3.12: PSS Cross-correlation Maxima in 100 Radio Frame

Figure 3.12 is also a proof that the timing synchronization acquired prior to this stage of processing has been maintained as least throughout the decoding of 100 LTE radio frames for PSS. Additionally, the repetitive pattern of PSS cross-correlation peaks with slow and slight changes in magnitude concurs with the recording setup of quasi-static channel.

3.4.2 Secondary Synchronization Signal

According to LTE radio frame structure, the locations of secondary synchronization signals are always one OFDM symbol before every primary synchronization signals. With the help of the location of the PSSs, it is not difficult to locate and decode all the SSSs.

In addition, due to the location arrangement of the PSS and the SSS in LTE radio frame structure, it is reasonable to assume that adjacent PSS and SSS experience the same channel condition from the base transceiver station to the recording device. Ergo, channel estimation calculated from each PSS can be used to compensate, to an extent, the influence that channel had impacted the SSS transmitted right before the respective PSS.

This compensation can provide valuable assisstance when decoding $s_1^{(m_1)}(n)$ and $s_0^{(m_0)}(n)$ from decoded SSS since these two sequences are m-sequences and do not possess high auto-correlation property as seen in Zadoff-Chu sequence.

The decoded $s_1^{(m_1)}(n)$ and $s_0^{(m_0)}(n)$ are processed in pairs in order to determine the transmitted $N_{ID}^{(1)}$. According to the definition of secondary synchronization signal in 3GPP specification 36.211, if SSSs s_1 and s_2 are sequentially scheduled in one LTE radio frame, e.g. (s_1, s_2) as in s_1 appears as the first SSS and s_2 the second, there will be no SSSs sequentially scheduled in one LTE radio frame as (s_2, s_1). This property helps decide the $N_{ID}^{(1)}$ that is used for the data recorded as well as deliver further information about frame timing. Namely, with the information $N_{ID}^{(1)}$ of derived from SSS, the beginnings of each radio frame can be located in recorded data.

Notice that it is only necessary to decode the even-numbered entry of secondary synchronization signal sequence as defined in Equation 2.3. Because the information derived thereafter is enough to calculate $N_{ID}^{(1)}$. And it is unnecessary to use SSSs to carry channel estimation when fully decoded PSSs are closely located.

3.5 Decoding Reference Signals and Channel Estimation

Similarly, reference signals can be located with the information of radio frame start and OFDM symbol timing which are acquired through reception steps explained in previous sections.

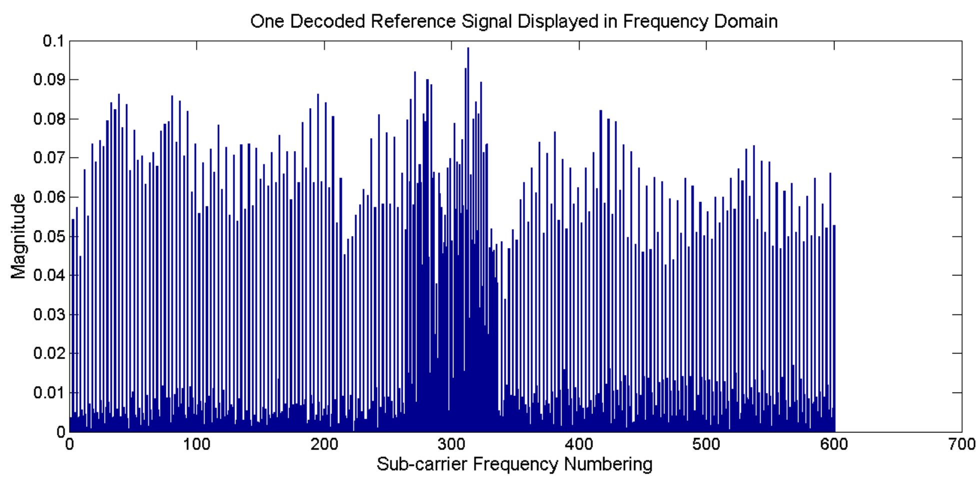

Figure 3.13: One Decoded Reference Siganl Displayed in Frequency Domain

Figure 3.13 shows the reference signal following the first deteced PSS in frequency domain. It is noticeable that the central 62 sub-carriers contain relatively high magnitude with a higher density comparing to rest of the sub-carriers in the system band. This phenomenon is caused by the delayed verision of the PSS prior to this reference signal.

If one takes a closer look at the parts of the signal with normal density of high magnitude, as shown in Figure 3.14, it can be observed that adjacent sub-carrier frequencies which are occupied by reference signal are twice of the sub-carrier spacing from each other.

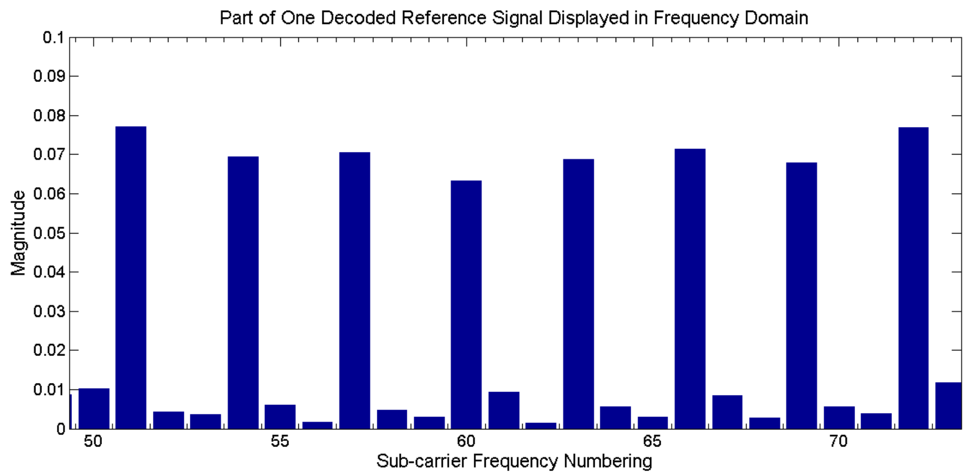

Figure 3.14: Part of One Decoded Reference Signal Displayed in Frequency Domain

Bearing this information in mind and combining it with the fact, as shown in Figure 3.2, that there are two OFDM symbols with dominating power transmitted every LTE radio slot, it can be inferred, according to 3GPP specification, that two antenna ports are used for transmitting the data recorded.

With all this information derived above, a channel estimation of the whole LTE system band for certain OFDM symbol duration can now be obtained.

3.6 Discussion About the Results

3.6.1 Lessons Learnt

- It is of vital importance to gather enough information on the object of interest prior to the measurement. Much time would be saved if the exact location of the commercial LTE base stations were determine prior to the data-recording.
- It can increase the efficiency to establish a coding convention and program structure before coding. In this project particularly, the code was re-organized in the middle of the project in order to improve its readablity, which could be avoided. Also, as the code grew in length, the naming of many similar variables became confusing due to the lack of pre-determined coding convention.

3.6.2 Pros and Cons

Pros

- Only one receiver chain is needed to finish this project, which means the highest sample rate offered by the software radio can be applied, hence highest possible accuracy can be achieved which is bounded by the hardware constraint.
- The receiver can be customized flexibly. This means further development of the project can be achieved relatively easily.

Cons

- It is difficult to determine the presense of LTE singals with the employed measurement setup. It takes a long time to set up and warm up the measurement system. It may take quite some time to detect steady transmission if the transmitting LTE base station is not in sight.
- The measurement setup hampers mobility. The measurement setup resembles a desktop computer, which takes much room to operate and requries large power source if no available electricity mains nearby.

3.6.3 Tricky Parts

The sampling rate offered by the software radio can cause inaccuracies with the receiving chain due to the fact that an OFDM symbol may not be represented by an integer number of recorded samples. It is troublesome to compensate for these inaccuracies.

The demodulation of recorded data is not straightforward as a consequence of the combination of software radio sampling rate and the need to retrieve the modulated content within each resource element.

3.6.4 Real-Time Implementation

Depending on the criteria of real-time computing, it is possible to implement a similar system to produce channel charaterization results within a short period of time after receiving the LTE signals, only, in addition to recording, the software radio program needs to be updated to handle the processing of data as well.

3.6.5 Performance

With a MacBook Air 2012 i5 1.8 GHz edition, it takes about 3.7 seconds to initialize the processing program and 65 seconds to process 100 frames of recorded LTE signals.

3.7 Conclusion

A spectrum analyzer program is used on a software radio system to detect the presense of FDD LTE downlink transmission. The bandwidth of the transmission is read from the spectrum analyzer program. When the presense of the transmission is confirmed, recording of transmitted FDD LTE downlink signals is made with the same software radio.

The transmission bandwidth read from the spectrum analyzer program is validated with the recorded signals. Then a series of fundamental parameters, i.e. the length of an OFDM symbol with normal cyclic prefix, were calculated using the recorded samples as unit. With the knowledge of these fundamental parameters, the coarse timing synchronization of the recorded signals is performed using the cross-correlation property of the cyclic prefix in OFDM symbols. The result of this synchronization is the location of the start of an OFDM symbol within the first slot of the recorded signals. Afterwards, a synchronization of the frame timing is preformed which produces the information of the location of a certain OFDM symbol within the FDD LTE downlink frame structure. The method used here is the demodulation of synchronization signals in LTE which contain information capable of indicating the beginning of a radio frame in LTE. With the synchronization signals demodulated and decoded, the reference signals in the recorded signals can be located, demodulated and decoded as well. Given the knowledge of the propagation channel and proper interpolation, an estimate of the transfer function across the whole bandwidth of the FDD LTE downlink transmission can be established.

Therefore, this report shows that it is feasible to carry out channel charaterization for LTE eNodeBs using LTE physical signals and a recording/processing machine. This conclusion opens the door for further work based on the findings of this project, i.e. direction locating using multiple receiving antennas/chains.

References

[1] Hyung G. Myung. Technical overview of 3gpp long term evolution. Technical report, Qualcomm/Flarion Technologies, 2008.

[2] Jim Zyren. Overview of the 3gpp long term evolution physical layer. Technical report, Freescale, 2007.

[3] Erik Dahlman, Stefan Parkvall, Johan Sköld, and Per Beming. *3G Evolution: HSPA and LTE for Mobile Broadband*. Academic, 2007.

[4] 3GPP. *3GPP TS 36.211 V8.9.0 (2009-12)*.

[5] Jan-Jaap van de Beek, Magnus Sandell, and Per Ola Brjesson. ML Estimation of Time and Frequency Offset in OFDM Systems. *IEEE Transcations on Signal Processing*, Vol. 45(No. 7), July 1997.

[6] Pei-Yun Tsai and Hsiang-Wei Chang. A New Cell Search Scheme in 3GPP Long Term Evolution Downlink OFDMA Systems. *2009 International Conference on Wireless Communications & Signal Processing*, pages 1–5, 2009.