Network Time Synchronization in Time Division - LTE systems

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ABSTRACT OF THE
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Network time synchronization is a requirement for TD-LTE systems to prevent multi-access and cross-slot interference. Network listening is a technique used for network time synchronization in femto cellular networks. However, femto BSs which use network listening technique for synchronization suffer from interference coming from neighboring femto BSs. In this thesis the possibility to coordinate the reception times of the non-synchronized femto BSs is investigated so as to combat the interference issues in network listening based synchronization for TD-LTE femto BSs. This coordination effectively reduces the interference among the non-synchronized femto BSs and thereby enables the network to converge to a common frame timing. Further coordinated reception is combined with and compared to coordinated transmission methods. Also a proof of concept implementation of a simple network time synchronization scheme based on network listening is done on a test bed with the help of Software Defined Radios (SDRs).

Keywords: Network time synchronization, Femtocells, TD-LTE, SDR, testbed, USRP

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Vishnu Prasad Kaushik Ganesan

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List of Abbreviations

3GGP	3rd Generation Partnership Project
ADC	Analog to Digital Converter
API	Application Programming Interface
ARIB	Association of Radio Industries and Businesses
ATIS	Alliance for Telecommunications Industry Solutions
BPSK	Binary Phase-Shift Keying
BS	Base Station
CCSA	China Communications Standards Association
CIC	Cascaded Integrator Comb
CoMP	Coordinated Multi-Point transmission/reception
CP	Cyclic Prefix
DAC	Digital to Analog Converter
DL	Down Link
DSP	Digital Signal Processing
DwPTS	Downlink Pilot Time Slot
EPS	Evolved Packet System
ETSI	European Telecommunications Standard Institute
E-UTRA	Evolved UTRA
E-UTRAN	Evolved UTRAN
FDD	Frequency Division Duplexing
FFT	Fast Fourier Transform
FM	Frequency Modulation
FPGA	Field Programmable Gate Array
GPS	Global Positioning System
GSM	Global System for Mobile Communications
HeNB	Home enhanced NodeB
ID	Identifier
IDFT	Inverse Discrete Fourier Transform
IFFT	Inverse Fast Fourier Transform
IMT-A	International Mobile Telecommunications Advanced
IP	Internet Protocol
ISI	Inter-Symbol Interference
ITU	International Telecommunications Union
LTE	Long Term Evolution
LTE-A	LTE-Advanced
MBSFN	Multicast-Broadcast Single Frequency Network
MIMO	Multiple-Input Multiple-Output
NL	Network Listening
NodeB	NodeB ,a logical node handling transmission/reception in multiple cells. Commonly, but not necessarily, corresponding to a base station
OFDM	Orthogonal Frequency-Division Multiplexing
OFDMA	Orthogonal Frequency-Division Multiple Access
OTA	Over The Air

PSS	Primary Synchronization Signal
QAM	Quadrature Amplitude Modulation
RB	Resource Block
RF	Radio Frequency
SC-FDMA	Single Carrier Frequency-Division Multiple Access
SDR	Software Defined Radio
SINR	Signal to Interference plus Noise Ratio
SSS	Secondary Synchronization Sequence
TDD	Time Division Duplexing
UE	User Equipment
UHD	USRP Hardware Driver
UL	Up Link
UpPTS	Uplink Pilot Time Slot
USRP	Universal Software Radio Peripheral
UTRA	Universal Terrestrial Radio Access
UTRAN	Universal Terrestrial Radio Access Network
TD-LTE	Time Division LTE
WCDMA	WideBand Code-Divsion Multiple Access

List of Notations

$a_k^{(m)}$	Modulation alphabet during the mth OFDM time interval
H_{synch}	Synchronization threshold
N	Noise power
N_c	Number of subcarriers
N_u	Length of Cyclic Prefix
N_{ID}^1	SSS uniquely defined from 0 to 167
N_{ID}^2	PSS uniquely defined from 0 to 2
N_{ID}^{cell}	Physical layer cell identity
P_{ij}	Received power at BS i from BS j
s_k	Complex symbol
S_n	IFFT output in time domain
T_u	OFDM Symbol duration
u	Zardoff-chu root index
x_k	kth modulated subcarrier
γ_{ij}	SINR at BS i from BS j
Δf	OFDM subcarrier spacing
Δt	Synchronization accuracy

1 Introduction

1.1 Overview

Cellular communication has had an exponential growth in the past decade and it promises to grow even more in the coming decades. Increase in the number of subscribers has resulted in the increase in data traffic and congestion. Also there is severe shortage of available frequency resources for mobile communications. The frequency allocations are handled by government agencies and they are sold at exorbitant prices. Therefore there is severe shortage of available resources on one side and an exploding user traffic on the other. This situation calls for the need of advanced communication techniques in order to combat the issues of capacity and poor indoor coverage in mobile networks. Also, efficient and judicious spectrum utilization methods must be adopted so as to handle spectrum shortage issues. There are several solutions proposed to overcome the above mentioned challenges in mobile communications.

In the coming years it is estimated that much of mobile data activity will occur indoors [1]. Low power nodes such as picocells and femtocells will complement the macrocells by filling up the coverage holes of the macrocell networks. A network that consists of a mix of macrocells and low power nodes are referred to as Heterogeneous networks [2]. Femtocells are low power indoor base stations (BS) which are capable of providing high throughput over a small coverage area. The problem of poor indoor coverage and reduced indoor capacity can be overcome by the use of femtocells. Long Term Evolution (LTE) is a solution proposed by the 3rd Generation Partnership Project (3GPP) to meet the capacity requirements. LTE uses Orthogonal Frequency Divison Multiplexing (OFDM) as its multiple access technique.

LTE supports both Frequency Division Duplexing (FDD) and Time Divison Duplexing (TDD). TDD turns out to be a more attractive option since it requires only an unpaired spectrum for operation which is beneficial considering the scarcity of frequency resources. Spectrum utilization is higher in TDD and it is well suited for small cells operating in higher frequency bands [3]. TDD also provides the flexibility of asymmetrical Down Link (DL)/Up Link (UL) ratio which is advantageous. LTE heterogeneous networks offers a plausible solution in handling the issues of capacity and poor indoor coverage. Specifically, heterogeneous network using Time Division-LTE (TD-LTE) seems to offer more flexibility in achieving this goal. TD-LTE femtocells provide an inexpensive alternative to expensive macro BSs.

When multiple nodes in a network have coordinated their transmission and reception time intervals in an organized manner, they are said to be network time synchronized. Network time synchronization is a requirement for TD-LTE systems to prevent multi-access and interslot interference [4]. Time synchronization is also required to share the time domain resources in the network in an unobstructive manner [5]. Network listening is a technique used for network time synchronization in a femto cellular network. In this method a femto BS is synchronized directly with another femto BS, based on BS-BS measurements. Network time synchronization using network listening is the recommended technique for a local area indoor TDD femtocell network by 3GPP [6]. However, femto BSs which use network listening technique for synchronization suffer from interference which comes from neighboring femto BSs. This prevents the entire network from getting synchronized.

Previously various techniques were investigated to improve network listening technique for synchronization in the case of femto BSs [7]. Fully orthogonal synchronization is one such network listening technique for synchronization. In fully orthogonal synchronization the synchronization signals are transmitted using orthogonal resources, which reduce interference to a non-synchronized femto BS. However, the non-synchronized femto BS receives interference from other non-synchronized femto BSs thereby preventing the entire network from achieving time synchronization.

1.2 Objective and scope of thesis

The objective of this thesis work is to investigate network time synchronization in TD-LTE femtocellular network. The scope of this thesis work is to use hierarchical master-slave approach based on network listening combined with coordinated reception for achieving network time synchronization. Also, an implementation of hierarchical master-slave approach based on network listening is done using Software Defined Radio (SDR).

1.3 Thesis organization

This Thesis is organized in the following manner. Chapter 2 gives an overview of network time synchronization in TD-LTE systems. It introduces the concept of LTE and explains the underlying concepts of OFDM systems. Different interference scenarios in TD-LTE networks are discussed and an overview into network time synchronization in mobile communication is also introduced here. This chapter concludes with details regarding network time synchronization in TD-LTE systems.

Chapter 3 investigates the concept of coordinated reception and proposes a novel approach of combining coordinated transmission with coordinated reception in order to overcome the interference barriers which divide the network into multiple connected components.

Proof of concept implementation of the network time synchronization scheme is demonstrated with the help of a test bed. Chapter 4 gives an introduction to SDR and Universal Software Radio Peripheral (USRP) boxes which are used as SDRs. This chapter also explains the test setup which was used to implement TDD link synchronization and network time synchronization. Detailed description of the algorithms used in achieving TDD link and network time synchronization in the test bed is also discussed.

Chapter 5 provides the results of the implementation of coordinated reception combined with coordinated transmission and also analyzes them. Measurements from the hardware implementation of TDD link synchronization and network time synchronization are provided and they help in verifying the performance of the implementation.

Chapter 6 concludes this thesis work by summarizing the algorithms implemented in order to overcome the network time synchronization issues in TD-LTE femtocells.

2 An overview of network time synchronization in TD-LTE systems

Network time synchronization refers to the time alignment of all the nodes in the network to a common time scale. In this thesis, network time synchronization schemes are discussed in reference to a LTE system. LTE has specific synchronization sequences which are used for the purpose of acquiring timing information. In order to understand the physical layer implementation of synchronization sequences in LTE, it is important to understand the physical layer transmission techniques in LTE. Subsection 2.1 will give a brief introduction into LTE physical layer.

2.1 An introduction to LTE systems

3GPP is a standardizing body which produces specification that defines the 3GPP technologies. It is an amalgamation of six standardizing bodies such as ARIB, ATIS, CCSA, ETSI, TTA and TTC. The main focus of 3GPP is to produce global technical specifications for various 3GPP technologies which include Global System for Mobile Communications (GSM), Universal Terrestrial Radio Access (UTRA) and Evolved-UTRA (E-UTRA) [8]. Release 8 of 3GPP defined LTE. The first LTE release offers upto 300Mb/s of data rate and a less than 5ms radio-network delay [9].

LTE was the iterative improvement of the 3rd Generation (3G) system which was based on Wide Band Code Division Multiple Access (WCDMA). As defined by the 3GPP, LTE offers a new multiplexing scheme *viz.* OFDM which provides higher data rates and is more spectral efficient.

2.1.1 Multiple access scheme in LTE

As mentioned previously, LTE uses OFDM transmission in which data is transmitted on a large number of parallel subcarriers. LTE employs Orthogonal Frequency Division Multiple Access (OFDMA) in Downlink (DL) and Single Carrier Frequency Division Multiple Access (SC-FDMA) in the Uplink (UL) direction. OFDM transmission can be considered as a multi-carrier transmission in which data is simultaneously sent on parallel orthogonal subcarriers. The subcarriers are of equal width and are separated with equal frequency $\Delta f = \frac{1}{T_u}$ spacing as shown in Figure 1. T_u is the OFDM symbol duration [8].

From [8] the OFDM modulator can be expressed using the complex baseband notation as shown in equation (2.1). The OFDM signal *x(t)* is defined during the interval $(m)T_u \leq t < (m+1)T_u$. In equation (2.1) x_k refers to the kth modulated subcarrier and $a_k^{(m)}$ refers to the modulation alphabet during the mth OFDM time interval. The modulation alphabet can be drawn from any modulation scheme such as BPSK,16QAM or 64QAM.

$$x(t) = \sum_{k=0}^{N_c-1} x_k(t) = \sum_{k=0}^{N_c-1} a_k^{(m)} e^{j2\pi k \Delta f t} \tag{2.1}$$

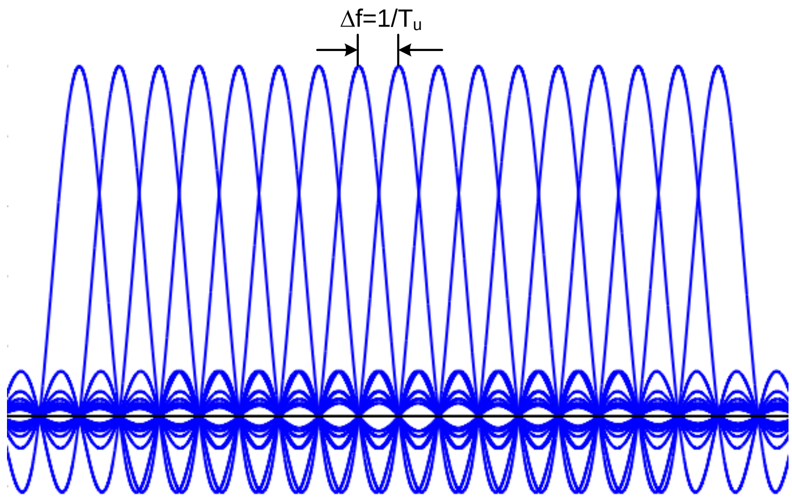

Figure 1: OFDM subcarrier spacing, from [8].

From equation (2.1) we can understand that during each OFDM symbol interval, N_c symbols are transmitted simultaneously in N_c orthogonal parallel subcarriers. In 3GPP specifications, two different subcarrier spacings are defined. The subcarrier spacing of Δf=15kHz is defined for regular transmission and a narrower Δf=7.5kHz is defined specifically for supporting Multimedia Broadcast Multicast Service (MBMS) [10]. In this thesis work, subcarrier spacing of Δf=15kHz is considered. OFDM modulator is implemented by using N-point Inverse Discrete Fourier Transform (IDFT). The input to the IDFT block is N_c complex symbols which are mapped onto N_c subcarriers as shown in equation (2.2). The output of the IDFT produces the discrete time domain signal which is then passed through a Digital to Analog Converter (DAC) and is then transmitted at the carrier frequency. A faster and more efficient way of implementing IDFT is by using Inverse Fast Fourier Transforms(IFFT) and it is used instead of IDFT for generating the time domain signal.

$$S_n = \sum_{k=0}^{N_c-1} s_k \, e^{\frac{j2\pi nk}{N_c}} \quad , \; n=0,1, \; \ldots \; , \; N_c\text{-}1 \tag{2.2}$$

Figure 2 explains the implementation of OFDM modulator at the transmitter side. Due to the time-dispersive nature of the wireless channel, the orthogonality between the subcarriers might be lost [8]. Also due to multipath propagation there will be Inter-Symbol Interference (ISI). Hence in order to eliminate these effects Cyclic-Prefix (CP) is inserted in front of the OFDM symbol as shown in Figure 3. The last N_u samples from the time domain signal block S_n is added to the front of it. Hence the total length of the OFDM symbol increases to $N_c + N_u$. CP causes a decrease in the data rate due to the addition of redundant data to the OFDM symbol. Therefore it is better to have a short CP. Addition of the CP makes the convolution between the input and channel impulse response circular [12]. The CP

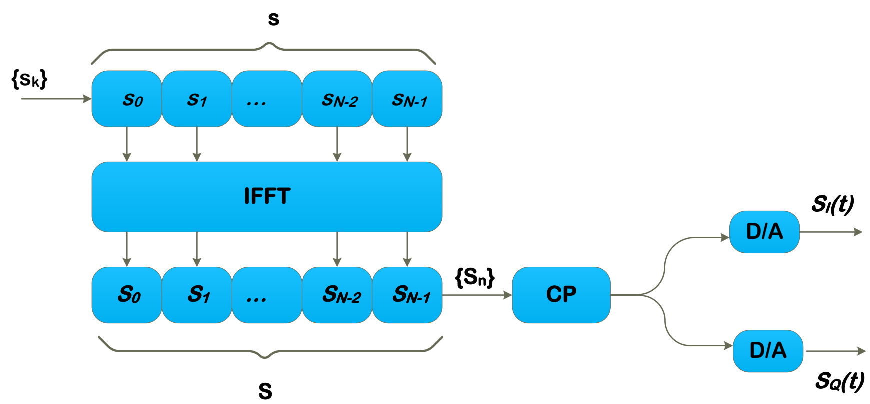

Figure 2: Basic OFDM transmitter, from [11].

adds a guard interval and prevents the previous transmitted symbol to overlap with the current symbol and hence effectively prevents ISI.
In LTE, for Δf = 15kHz there are two possible CP lengths provided [13].

- Normal cyclic prefix:N_u= 160 × T_s(OFDM symbol # 0), N_u =144 × T_s (OFDM symbol # 1 to # 6)
- Extended cyclic prefix:N_{ue} = 512 × T_s(OFDM symbol # 0 to # 5), Where T_s = 1/2048 × Δf

The normal version of the CP is used for small cell environments where high data rates are required. Normal CP will provide smaller overheads and there by provide higher data rates. The extended version of CP is used in larger environments with extreme time dispersion. Hence, extended CP is used for multi-cast transmissions. [8]. In this thesis work since small cell environments are considered, normal CP length is assumed.

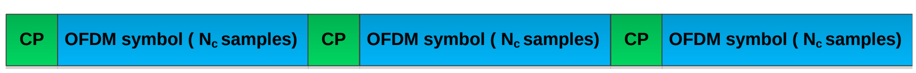

Figure 3: Cyclic prefix added to the OFDM symbol.

The OFDM receiver block diagram is shown in Figure 4. The received analog complex baseband signal passes through an Analog to Digital Converter (ADC). The sampling interval is $\frac{T_u}{N_c}$. After removing the CP, the resultant samples are passed through Fast Fourier Transform (FFT) block to convert the samples into frequency domain. After this, post processing is done on these samples in order to extract the data. Though the OFDM transmission offers a lot of advantages, it has some shortcomings such as sensitivity to frequency offset and high Peak to Average Power Ratio (PAPR). High PAPR increases the power consumption [12] and therefore OFDMA technique is not suitable for User Equipment (UE) which has limited power supply. Hence a more power efficient SC-FDMA scheme is used at the UE.

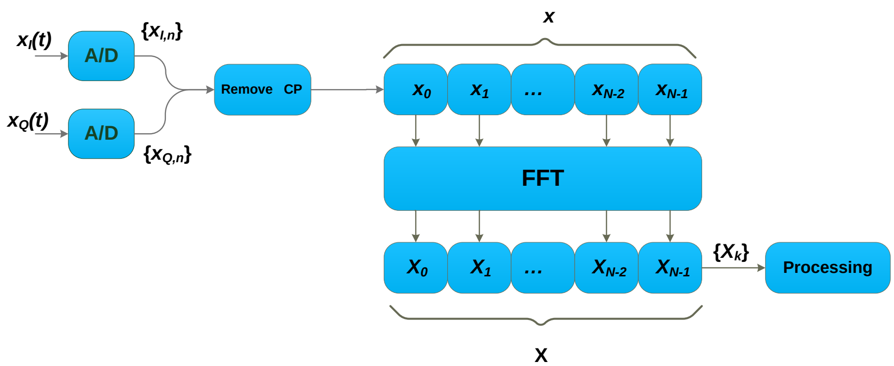

Figure 4: Basic OFDM receiver, from [11].

2.1.2 Flexible bandwidth and duplexing in LTE

Frequency spectrum is a vital resource for mobile communications. Due to its limited availability, the spectrum allocation is handled by government agencies. The spectrum allocation differs in different geographical locations and it should accommodate the operations of different radio access technologies in the same geographical region. Multiple access schemes controls the sharing of the spectrum by multiple users while the duplexing schemes dictate the conditions by which the BS and UE share the spectrum for DL and UL transmissions. LTE makes use of both paired and unpaired spectrum as shown in Figure 5. Paired spectrum is used for FDD and an unpaired spectrum is used for TDD.

In FDD, the DL and UL transmissions occur in different parts of the spectrum and hence the requirement of a paired spectrum. Whereas in TDD, both the UL and DL transmission happen in the same band but at different times instances. Therefore an unpaired spectrum is sufficient for TDD operation. LTE also supports half-duplex FDD where the BS and UE communicate in different bands and at different times [8]. The striking feature of LTE is that the multiple access technology is the same for both FDD and TDD operations. The other key feature of LTE is that it provides flexible transmission bandwidths. LTE is able to provide transmission bandwidth in the range between 1.4MHz to 20 MHz [9] as shown in Figure 6. This gives the flexibility to use the available bandwidth in an efficient manner based on traffic requirements.

2.1.3 Additional improvements in LTE-A

International Mobile Telecommunications Advanced (IMT-A) is the term used by International Telecommunication Union (ITU) for defining radio-access technologies beyond IMT-2000 [8]. ITU has set some specific requirements for systems based on IMT-A [14]. LTE release 8 was not able to entirely fullfill the requirements of IMT-A. 3GPP release 10 addressed the requirements which were defined in IMT-A and also included several additional enhancements to its release. Therefore release 10 was popularly called as LTE-Advanced (LTE-A). Though the name "advanced"

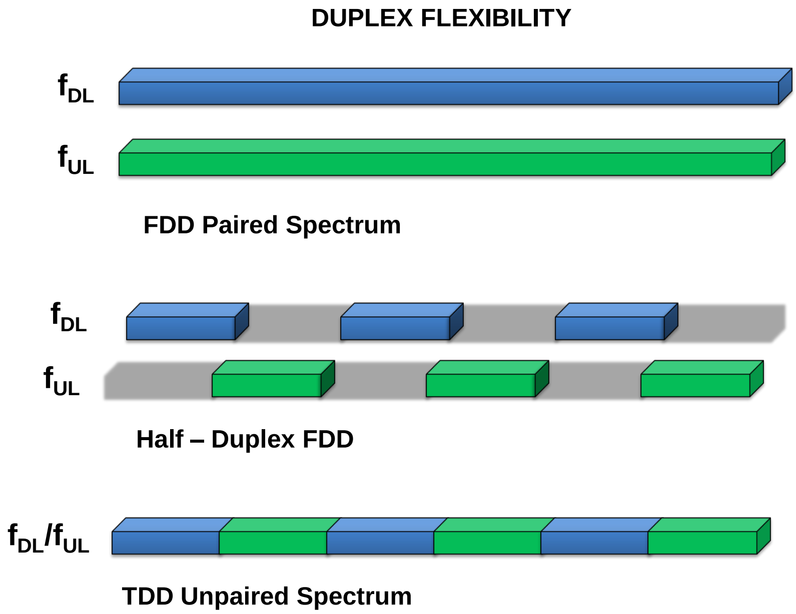

Figure 5: Duplexing in LTE, from [9].

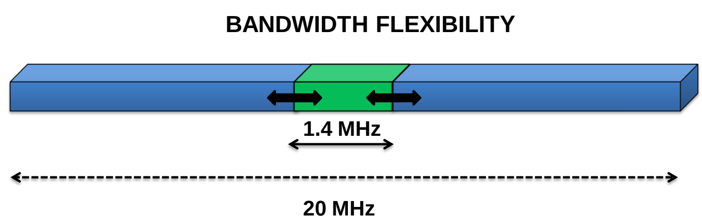

Figure 6: Flexible bandwidth in LTE, from [9].

might cause some confusion, it must be noted that LTE-A uses the same technology as LTE but, it has brought with it some additional capabilities [8]. LTE-A provides the following enhancements to LTE [15] :

- Carrier Aggregation to widen the bandwidth
- Supports Heterogenous Deployments
- DL spatial multiplexing using up to eight-layer multiple-input multiple-output (MIMO)
- DL intracell Coordinated Multi-Point transmission/reception (CoMP)
- UL Spatial Multiplexing using four-layer MIMO

2.1.4 LTE frame structure

In LTE, DL and UL transmissions are arranged in the form of frames of 10ms duration [16]. An LTE frame consists of 10 subframes each of 1ms duration. Each subframe has two time slots of 0.5ms duration, with each time slot carrying 7 OFDM symbols(with normal cyclic prefix). As mentioned previously, each OFDM symbol carries data simultaneously on N_c subcarriers and the subcarrier spacing is $\Delta f = 15kHz$. A resource block (RB) is the smallest frequency-time resource unit which is assigned to any user. For a normal cyclic prefix configuration with $\Delta f = 15kHz$ there are 12 subcarriers in one OFDM symbol duration and 7 such OFDM symbols forms a RB as shown in Figure 7.

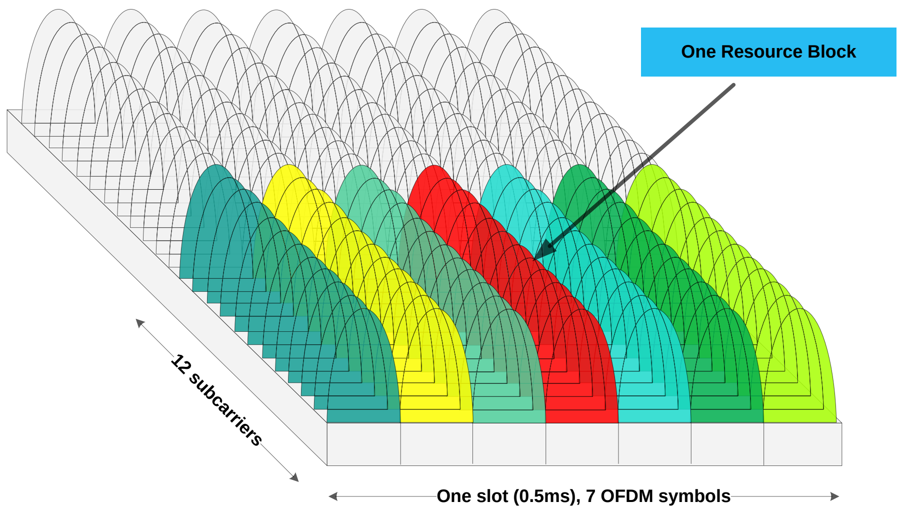

Figure 7: LTE resource block.

There two types of frame structures in LTE. Type 1 refers to the FDD frame structure and Type 2 refers to the TDD frame structure. In the FDD frame as shown in Figure 8, there are 20 time slots (10 subframes) with numbering from 0-19. All the subframes in the frame are used in both DL and UL directions. The TDD frame structure differs from the FDD frame structure as shown in Figure 9. TDD LTE systems are generally labeled as TD-LTE systems. The TDD frame consists of two half frames each of 5ms duration. The subframe numbering starts from 0 in the TDD frame. Subframe 1 in the TDD frame is the special subframe. It contains 3 fields *viz.* Downlink Pilot Time Slot (DwPTS), Guard Period (GP) and Uplink Pilot Time Slot (UpPTS). The DwPTS carries the Primary Synchronization Signal (PSS) which is used for synchronization and some DL data. The UpPTS can be used by the UE for the purpose of random access. The special subframe enables the switching of transmissions from DL to UL.

The TDD frame structure offers the support for asymmetrical DL and UL transmission. This is advantageous in situations were we have varying loads in DL and UL. Seven different TDD frame configurations are provided to manage asymmetric traffic. The possible frame configurations are given in Table 1. From the table it can

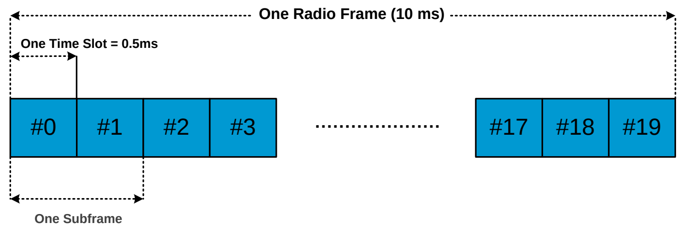

Figure 8: Type 1 FDD frame structure in LTE, from [16].

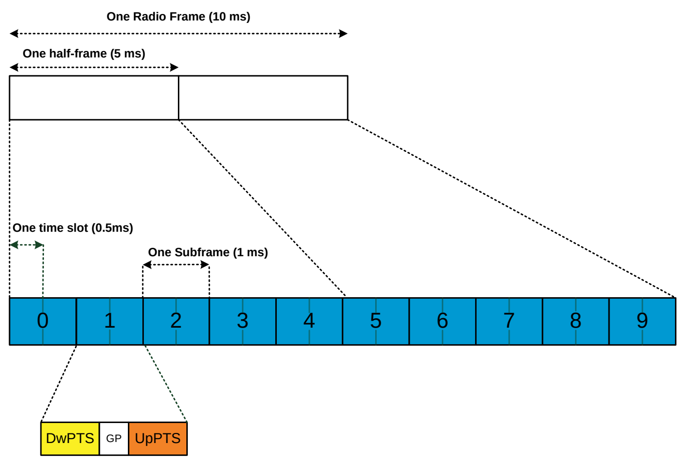

Figure 9: Type 2 TDD frame structure in LTE, from [16].

be seen that TDD frame comes in two flavors, one with 5ms switching periodicity and the other with 10ms switching periodicity. It can be noted that in the case of 5ms switching periodicity, there are two special subframes but there is only one special subframe in the case of 10ms switching periodicity.

Table 1: Uplink-downlink allocations, from [16].

UL/DL Configuration	**Period(ms)**	**Subframe**									
		0	1	2	3	4	5	6	7	8	9
0	5	D	S	U	U	U	D	S	U	U	U
1	5	D	S	U	U	D	D	S	U	U	D
2	5	D	S	U	D	D	D	S	U	D	D
3	10	D	S	U	U	U	D	D	D	D	D
4	10	D	S	U	U	D	D	D	D	D	D
5	10	D	S	U	D	D	D	D	D	D	D
6	5	D	S	U	U	U	D	S	U	U	D

2.2 Interference scenarios in TD-LTE systems

Intra-cell interference can be avoided to a large extent in LTE systems due to sub-carrier orthogonality in OFDM transmission. However, TDD transmissions within a cell are inherently prone to co-channel interference due to its duplexing arrangement. Since the DL and UL transmissions use the same frequency channel, but at different time instants, strict timing restrictions are imposed to avoid intereference between the DL and UL transmissions in a TD-LTE cell. However there are other possible interference scenarios which might occur between TD-LTE macrocells which could potentially harm the system. They are discussed in [17,18] and are briefly discussed here.

Intra-cell interference: In a TDD cell, if all the users are scheduled on the same set of resources, then there can be intra-cell interference. In a TD-LTE cell, theoretically different users are scheduled on different RB's by the scheduler and hence it is assumed that there is little or no intra-cell interference.

Inter-cell interference: When users in the adjacent cells are scheduled on the same RB's but with different DL/UL configuration, potentially harmful interference happens due to inter-cell interference. There are 4 possible scenarios as mentioned in [17]. These interference scenarios are briefly explained in the Figure 10. Synchronizing the base stations to a common time scale and by using the same TDD frame configurations with large guard time helps in preventing inter-cell interference [19].

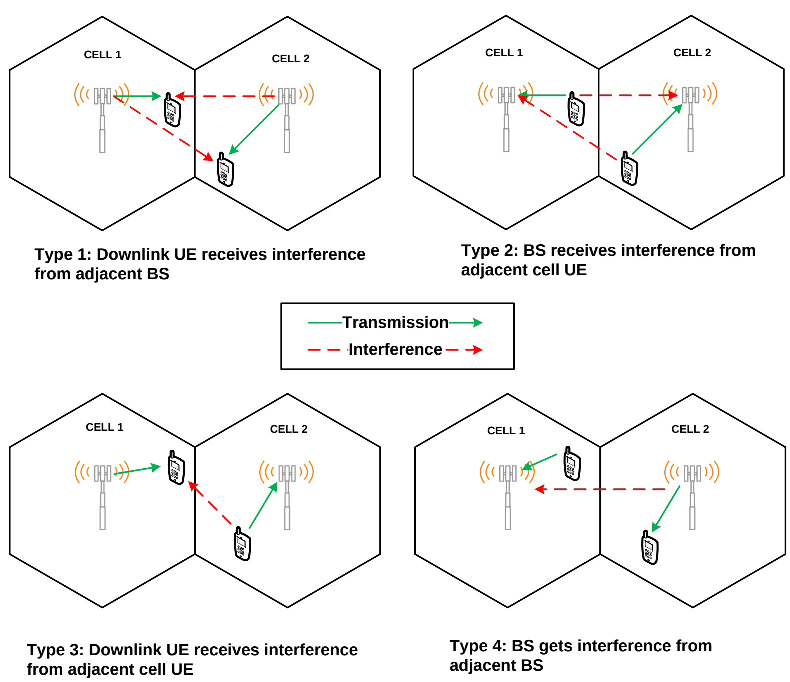

Figure 10: Inter-cell interference scenarios, from [17].

The different scenarios shown in Figure 10 are analyzed here. In Type 1 scenario cell 1 is assigned on a DL time slot and the adjacent cell 2 is also assigned on DL time slot at the same time. In this scenario, both the UEs on the cell edge receive interference from the neighbor BSs. In Type 2 scenario, both cell 1 and cell 2 is assigned an UL time slot. This results in the reception of weak interference at the BSs from the adjacent neighbor UEs. In Type 3 scenario, cell 1 is assigned DL time slot and cell 2 is assigned UL time slot. The cell edge UE in cell 1 experiences strong interference from the cell edge UE in cell 2. This is the most serious type of interference of all the cases mentioned here [18]. In Type 4 scenario, cell 1 is assigned on UL time slot and cell 2 is assigned DL time slot. The BS in cell 1 experiences interference from BS in cell 2. However the strength of interference is very low as the path loss between the BSs are high due to the large separation between them.

Cross-slot interference: This is a special case of inter-cell interference, in which interference arises due to different TDD frame configurations in the adjacent TD-LTE cells. Even if the cells are time synchronized, there will be interference due to the mismatch of DL and UL slots. An example of this is shown in Figure 11. Forcing all the cells to use the same TDD frame configuration will dilute the flexibility which the TDD frame offers through different configurations. At the same time, dynamic assignment of TDD frame configurations in different cells based on varying traffic load will also lead to severe interference situations. To overcome this dilemma, [19] offers two plausible solutions.

- Quick exchange of the messages between the base stations to dynamically coordinate the scheduling inorder to avoid cross-slot interference
- Usage of dynamic TDD frame configuration assignments only in low load conditions where the effects of inter-cell interference is less critical.

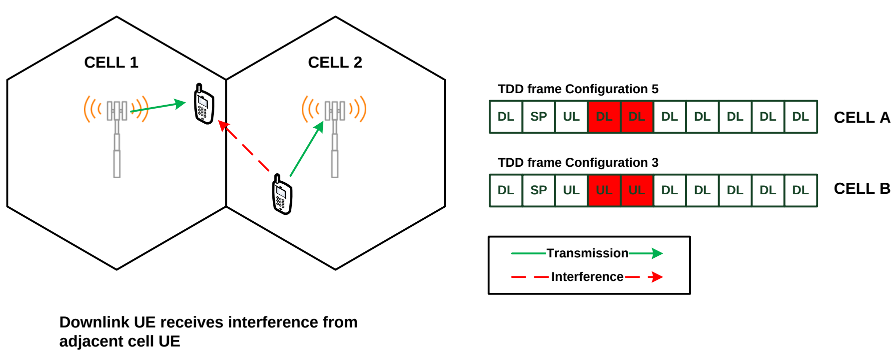

Figure 11: Cross-slot interference, from [17].

2.3 Network time synchronization in mobile communications

Network synchronization deals with the distribution of time and frequency over a network of clocks, spread over an even wide geographical area [20]. Network time Synchronization is an important aspect for TDD systems in advanced Evolved-Universal Terrestrial Radio Access Network (E-UTRAN) in order to prevent multi-access and cross-slot interference. A common notion of time must be available for all the nodes to coexist in the network. Additionally network time synchronization in TD-LTE systems provides significant performance gain in terms of cell throughput when compared to a non-synchronized network [21]. There has been extensive studies carried out on the network synchronization issue and several strategies have been discussed to achieve the same. The strategies are classified as shown in Figure 12.

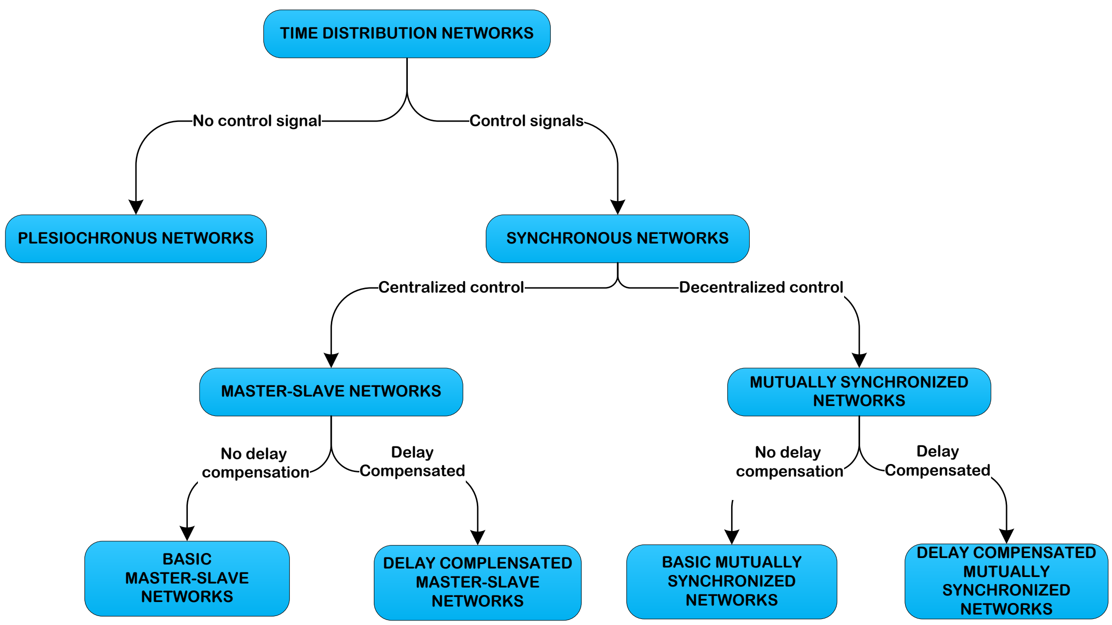

Figure 12: Network synchronization strategies, from [20].

2.3.1 Network synchronization strategies

Three popular strategies as shown in Figure 13 are discussed in [22]. These methods are briefly introduced here.

Full plesiochrony (Anarchy): This refers to the case of Anarchy in the network, where there is no coordination between the nodes and each node has its own clock. As shown in Figure 12 there are no control signals involved here.The clear advantage in these type of systems is that they are robust to node failures. Since the clocks of

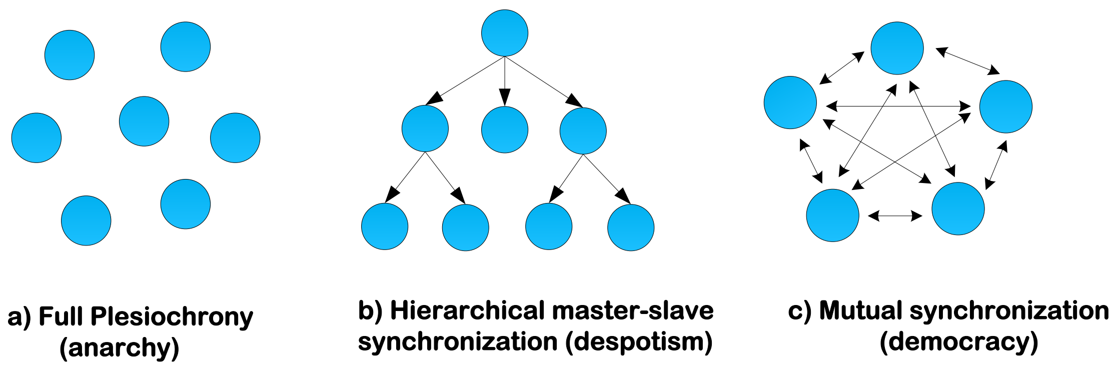

Figure 13: Popular network synchronization strategies, from [22].

the nodes are independent of each other, in case of a node failure, it doesn't affect the entire network. The disadvantage in this case is that high quality expensive clocks are required for each node which increases the maintenance costs [20].

Hierarchical master-slave synchronization (Despotism): As shown in Figure 12, this comes under synchronous networks with centralized control. In this case, there is a master-slave relationship between the nodes in the network. Control signals are used for transmitting information related to timing. There is a root node which acts as the master, and the other nodes in the network listen to the master and acquire its timing. The slave nodes will acquire the timing from the master directly or indirectly as shown in Figure 13(b). The advantage of this strategy is the ease of implementation. A critical problem with this type of implementation is the loss of timing during node failure. If a particular slave node fails, then the other slave nodes which are attached to this node will loose the timing and will have to survey the spectrum to re-acquire synchronizations signals from a different node. This process of re-acquiring synchronization signal may turn out to be futile if the slave node is not able to hear the nearby neighbor node due to high interference. The other issue arises when the master node fails and thus collapsing the timing of the entire network below the master. This problem can be partially overcome by having multiple master nodes in a network [20].

Mutual synchronization (Democracy): This is an example of decentralized synchronization. Mutual Synchronization strategy adopts a democratic approach to align the clocks and bypasses the need of a master clock. As shown in the Figure 13(c) the nodes try to listen to one another in order to obtain the synchronization signal. One of the biggest advantage of mutual synchronization is its distributed decentralized nature and the fact that there is limited overhead in the control signals [23]. The complexity associated with the implementation and the fact that the network stability is governed by path delay dynamics turn out to be the limiting factors of this strategy [20].

2.3.2 Network time synchronization in TD-LTE

Network time synchronization is a critical requirement of TD-LTE systems. The performance of network time synchronization in TD-LTE systems have been studied in [21]. It has been shown that network time synchronization improves the network performance by improving the cell throughput. The benefits of network time synchronization [4] are summarized here:

- Network time synchronization helps in the use of various co-operative multipoint techniques such as beam forming etc.
- Inter-cell interference cancellation methods are greatly enhanced with the help of network time synchronization.
- In LTE relays asynchronous neighbor BSs will cause significant issues for relay operations. Network time synchronization will prevent the interference and improve the efficiency of relaying.
- LTE has support for Multicast/Broadcast over Single Frequency Network (MBSFN) frames. Network time synchronization is an important aspect for MBSFN transmissions as the transmissions happen from a set of synchronized BSs.

Physical layer aspects of network time synchronization in TD-LTE

The goal of this thesis work is to time synchronize the different BSs in the network to a common frame timing. The frame synchronization is done with an accuracy of Δt so as to avoid inter-cell interference. In LTE system, the normal CP has a duration of 4.7μs. At the receiver, if the timing offset of the received signal is within this duration, then the signal can be correctly decoded. Hence the target synchronization accuracy given by the CP is $\Delta t \leq 4.7\mu$s. Link synchronization in LTE between a BS and UE is achieved by using periodic transmissions of known synchronization sequences using the same resources used for data resources. UE acquires the frame timing by correlating the received signal with a known synchronization sequence. The synchronization sequences occupy a small portion of the time-frequency resources available in the cell. These sequences can be reused for the purpose of network time synchronization. In the case of network time synchronization, the non-synchronized BS will correlate the received synchronization sequences during a measurement interval so as to obtain the frame timing information of the synchronized BS. These measurement intervals will reappear in a periodic fashion so as to maintain the network time synchronization.

In LTE there are two types of synchronization sequences *viz.* Primary Synchronization Sequence(PSS) and Secondary Synchronization Sequence(SSS) which are used for synchronization. There are 504 unique physical layer cell identities in LTE. These identities are grouped into 168 unique groups with each group containing 3 unique identities [16]. A physical layer cell identity is given by $N_{ID}^{cell}=3N_{ID}^{(1)}+N_{ID}^{(2)}$ where $N_{ID}^{(1)}$ represents the SSS which is uniquely defined from 0 to 167 and $N_{ID}^{(2)}$

represents the PSS which is defined from 0 to 2. PSS is used for the identifying the cell identity within the group and SSS is used for identifying the group which the cell belongs to. In other words, PSS and SSS are used to pinpoint the exact BS from the 504 available uniquely available BSs.

The PSS signal is generated from a frequency domain Zadoff-Chu sequence according to equation (2.3) where the zardoff-chu root index u is given in Table 2. The PSS is transmitted by mapping the zadoff-chu sequence with five padded zeros on each end into the subcarriers in the frequency domain. In the TDD frame, the PSS is loaded on the third OFDM symbol in the special subframe.

$$d_u(n) = \begin{cases} \exp -j\frac{\pi u n(n+1)}{63} & n = 0, 1, ..., 30 \\ \exp -j\frac{\pi u(n+1)(n+2)}{63} & n = 31, 32, ..., 61 \end{cases} \quad (2.3)$$

Table 2: Root indices for the PSS, from [16].

$N_{ID}^{(2)}$	**Root index** u
0	25
1	29
2	34

The SSS signal is generated by interleaving of two length-31 binary sequences in the frequency domain. The result of which is scrambled with a scrambling sequence given by the PSS [16]. In TDD frame the SSS is transmitted in the last OFDM symbol of subframe 0 and 5. The SSS generated from two length-31 binary sequences are shown in equation (2.4) where indices m_0 and m_1 are derived from $N_{ID}^{(1)}$. *d(2n)* refers to SSS transmitted on the even numbered resource elements and *d(2n+1)* refers to SSS transmitted on the odd numbered resource elements. $s_0^{(m_0)}$ and $s_1^{(m_1)}$ are two different cyclic shifts of the m-sequence which are scrambled with binary scrambling code $c_0^{(n)}$ for the even numbered resource elements and with binary scrambling codes $c_1^{(n)}$, $z_1^{(m_0)}$ and $z_1^{(m_1)}$ for the odd numbered resource elements as shown in (2.4).

$$\begin{aligned} d(2n) &= \begin{cases} s_0^{(m_0)}(n)c_0^{(n)} & \text{in subframe 0} \\ s_1^{(m_1)}(n)c_0^{(n)} & \text{in subframe 5} \end{cases} \\ d(2n+1) &= \begin{cases} s_1^{(m_1)}(n)c_1^{(n)}z_1^{(m_0)}(n) & \text{in subframe 0} \\ s_0^{(m_0)}(n)c_1^{(n)}z_1^{(m_1)}(n) & \text{in subframe 5} \end{cases} \end{aligned} \quad (2.4)$$

3 Coordinated reception based synchronization for femtocell systems

3.1 Introduction

There has been an unprecedented exponential increase in wireless data traffic in the past few years which has paved way for heterogeneous networks. Heterogeneous networks includes the existing macro cells along with smaller cells such as pico BSs and femto BSs. These smaller cells fill up the coverage holes which exist in the macro-cellular network and also improve the capacity of the network [24]. Achieving network time synchronization will play an important role in delivering the promise made by such future heterogeneous networks. Network time synchronization is an important aspect for both distributed and centralized wireless systems such as sensor networks and TD-LTE systems. Network time synchronization is beneficial for techniques such as CoMP, inter-cell interference cancellation, relaying, positioning and mobility operations. 3GPP has identified three synchronization techniques for TD-LTE femto BS network time synchronization [6]. They are briefly described here.

Synchronization through Global Positioning System (GPS): In this technique, each femto BS has a GPS receiver inorder to acquire timing information. GPS receivers will provide the most accurate timing information required for synchronization. Since the femtocells are placed indoors, it is difficult for the GPS receiver to operate indoors and hence there is a limitation on using this technique. Also, the GPS receivers are expensive which increases the overall cost of the femtocell equipment.

Synchronization using IEEE 1588 v2: In this method, the synchronization signals are obtained through Ethernet/Optical fiber backhaul connections. This method can provide sub-microsecond level accuracy but this is limited by the fact that good backhaul conditions may not be always available.

Synchronization through network listening: When the above two methods fail to work, network listening is a good alternative for achieving network time synchronization. In this method a non-synchronized femto BS will derive its timing from a synchronized femto BS/macro BS by using Over The Air (OTA) measurements. Network listening proves to be a cost effective performance enhancement scheme. In this chapter we focus on improving the network listening technique for TD-LTE femtocells. The concept of network listening is illustrated in Figure 14.

Previous studies have been carried out to achieve synchronization using various protocols, to mitigate synchronization errors and clock drifts [25–29]. In Particular, network synchronization based on the hierarchical master-slave approach with a root node connected to the external clock, has been investigated in [26–29]. In LTE, known synchronization sequences are periodically transmitted to synchronize

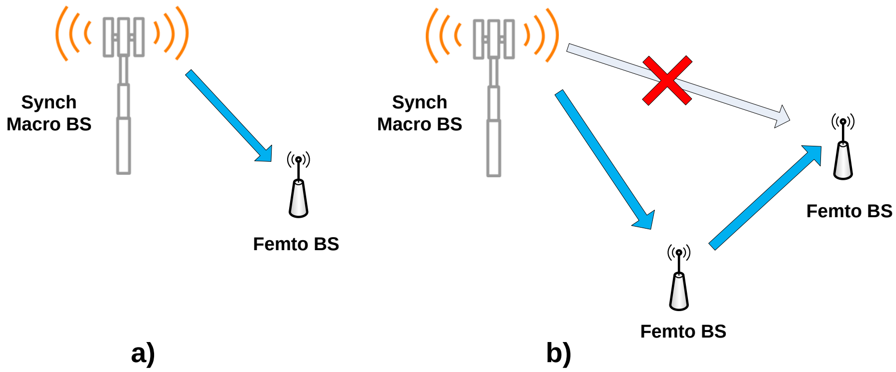

Figure 14: Synchronization using network listening, from [6].

the BSs and UEs. The same synchronization sequences can be used for the purpose of network time synchronization thus eliminating the need for using additional resources. As a result of this, trying to achieve network time synchronization through network listening would receive a lot of interference. Interference from both synchronous and non-synchronous BSs disturb a non-synchronous BS trying to synchronize to another BS. From this it can be understood that interference acts as a barrier to a non-synchronized femto BS which listens to synchronization signals thereby preventing the whole network from getting synchronized and thus results in splitting the network into multiple connected components as shown in Figure 15.

As a consequence, the BSs within a connected component cannot hear BSs outside its component. Within a connected component, multi-hop synchronization is possible. However in order to bridge the interference barriers between connected components, either UE assistance or coordination of transmitters and/or receivers is needed. Coordinating the transmission of synchronized nodes was discussed in [7]. However coordinating the transmission of synchronized nodes does not remove the interference which exists inside a non-synchronized connected component. Coordinating the reception times of the nodes was described in [6]. In coordinated reception, the subsets(connected components) of non-synchronous BSs coordinate and time align their measurement gaps(reception times) so as to listen to synchronization signals from other synchronized BSs. This will remove the interference barrier that exists between the connected components.

In this thesis work we investigate coordinated reception technique in which the interference experienced in network listening is reduced by coordinating the reception times of non-synchronous BSs. This chapter is arranged as follows. First we describe the system model which is used for system simulation. Second, we propose a detailed protocol for coordinated reception and then investigate the performance of such a protocol in a femto cellular network and finally we combine coordinated reception with coordinated transmission proposed in [7], and investigate the performance benefits of coordinated reception with coordinated transmission.

3.2 System model

The system model which is used for investigating the performance of coordinated reception technique is described here. It is assumed that N femto BSs, here after referred to as "BSs" in this chapter, periodically transmit synchronization signals in an asynchronous manner and try to synchronize themselves by receiving synchronization signals transmitted by their neighbors. It is also assumed that BSs serve UEs in their cells, transmitting all the time to UEs using e.g. shared channels, and that the resources used for transmitting synchronization signals are interfered by shared channel transmission in neighboring cells. This would happen in a cellular network, for e.g. in LTE. Thus when BS j is listening to the synchronization signal from BS i, there is interference from the transmissions of all other BSs. We don't consider spreading gain on decoding the received signal. We consider a local area femtocell network which tries to synchronize itself. Synchronization is based on a hierarchical master-slave approach. We assume that there is atleast one BS, also known as the root node, which is synchronized to the external clock and the remaining BSs try to listen to this BS and join it in a multi-hop fashion thereby resulting in the formation of a spanning tree.

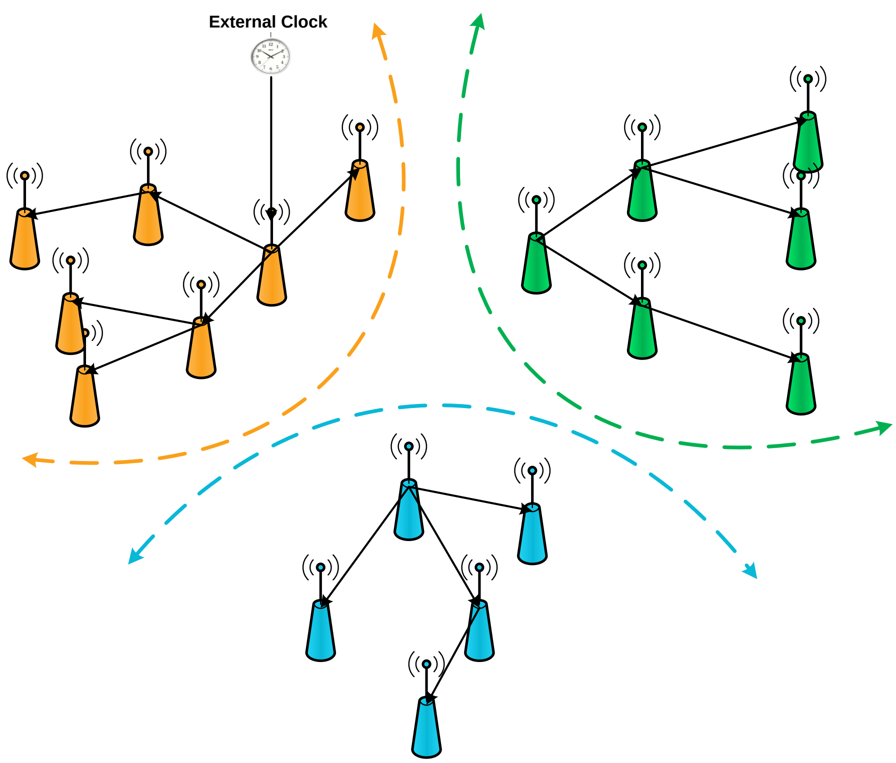

Figure 15: Presence of interference barriers.

The external clock timing for the root node may be obtained through a GPS receiver or by synchronizing to a macro BS. In a interference limited system such as LTE, there may be apriori multiple connected components in which the BSs within the components are synchronized to each other, but there exists interference barriers between these components which prevents the entire network from getting synchronized. Figure 15 depicts one such system where the network is divided into multiple connected components which includes a single tree synchronized to the external clock and multiple non-synchronized trees which are not connected to the external clock. The main motivation here is to apply coordinated reception technique in the non-synchronized trees so as to overcome the interference barrier and to form a single connected component which spans the whole network and is synchronized to the external clock.

The success of synchronization depends on the received signal to interference plus noise ratio (SINR) of the synchronization signal. We consider a threshold H_{synch}, i.e. when SINR $> H_{synch}$, we assume that synchronization is possible. Also, we assume that once a subset of BSs are synchronized, they may exchange messages in order to coordinate their actions to reduce interference. This coordination may be the coordinated transmission in a synchronized tree as discussed in [7] or by coordinating the reception which is the crux of this chapter. It is assumed that such kind of coordination among BSs happens instantaneously. Also possible problems that may arise due to duplexing issues are not addressed here. It is assumed that the BSs may reserve sufficient time for synchronizing themselves along with serving its UEs.

3.3 Techniques to improve network listening synchronization

Network listening suffers from interference as the channel that synchronization signals are transmitted on, overlap with transmissions on other channels by neighboring BSs. Since the BSs transmit continuously, when a non-synchronous BSs tries to synchronize to another BS it receives interference from both synchronous and non-synchronous BSs. The SINR at BS i, which is trying to synchronize with other BS j is given in the equation (3.1) where P_{ij} is the received power at BS i from BS j, U is the set of all BSs and N is the noise at the receiver.

$$\gamma_{ij} = \frac{P_{ij}}{\sum_{k \epsilon U,\, k \neq j} P_{ik} + N} \tag{3.1}$$

3.3.1 Coordinated transmission to improve network listening

Techniques to improve the hierarchical master-slave synchronization based on network listening were discussed in [7]. This includes stratified, fully orthogonal and macro diversity. Stratum level indicates the distance between the slave BS and the root BS in a hierarchical master-slave spanning tree. In stratified synchronization, the interference comes only from BSs which are in the same stratum level of the interfered BS while it receives no interference from the other stratum levels. In macro diversity all the BSs transmit the synchronization signals simultaneously, thereby effectively increasing the transmission power and removing the interference. In the fully orthogonal transmission technique the BSs within a connected component coordinate their transmissions by orthogonalizing their transmission and thus removing the interference experienced by an external BS trying to listen to this connected component.

Fully orthogonal transmission technique will be used here to coordinate the transmissions within a connected component in order to achieve synchronization. The orthogonalization of the transmissions can be realized by multiplexing the transmissions of the different BSs in time domain, within a connected component. Equation (3.2) gives the received SINR at BS i and shows how fully orthogonal transmission removes interference for an external BS i not part of the connected component T_j, when it listens to a BS j which is inside a connected component T_j. P_{ij} is the received power at BS i from BS j, U is the set of all BSs and N is the noise at the receiver.

$$\gamma_{ij} = \frac{P_{ij}}{\sum_{k \epsilon U,\, k \neq j} P_{ik} - \sum_{l \epsilon T_j} P_{il} + N} \tag{3.2}$$

3.3.2 Coordinated reception by synchronizing measurement gaps

Synchronizing and coordinating the measurement gaps of all the BSs within a connected component will greatly reduce the interference within a connected component and thereby enabling the BSs to listen to synchronization signals from outside their connected component. Further coordinated reception is combined with fully orthogonal transmission and is compared with other coordinated transmission methods.

- **Coordinated reception :** With the help of inter BS communication, it is possible to coordinate the reception times of different BSs within a connected component which will allow them to track the BSs which are outside their component and thereby paving the way to listen to an external BS which is connected to the external clock. Equation (3.3) gives the received SINR at a BS i from connected component T_i when it listens to another BS j which belongs to connected component T_j. It has to be noted that in connected component T_i coordinated reception has been implemented. P_{ij} is the received power at BS i from BS j, U is the set of all BSs and N is the noise at the receiver. It can be noted in (3.3) that due to coordinated reception in connected component T_i, the interference within the connected component has been removed.

$$\gamma_{ij} = \frac{P_{ij}}{\sum_{k \epsilon U,\, k \neq j} P_{ik} - \sum_{m \epsilon T_i} P_{im} + N} \tag{3.3}$$

- **Coordinated reception with fully orthogonal transmission:** Coordinated reception effectively removes the interference within a connected component. But there still exists interference from synchronous connected components which are outside. Hence it is proposed that by combing coordinated reception and fully orthogonal transmission, interference from both non-synchronous and synchronous sets of BSs can be removed. Equation (3.4) gives the received SINR at a BS i from connected component T_i when it listens to another BS j which belongs to connected component T_j. Coordinated reception is implemented in connected component T_i and fully orthogonal transmission is implemented in connected component T_j. Equation (3.4) clearly demonstrates the performance of this interference removal scheme. P_{ij} is the received power at BS i from BS j, U is the set of all BSs and N is the noise at the receiver.

$$\gamma_{ij} = \frac{P_{ij}}{\sum_{k \epsilon U,\, k \neq j} P_{ik} - \sum_{m \epsilon T_i} P_{im} - \sum_{l \epsilon T_j} P_{il} + N} \tag{3.4}$$

3.4 Protocol for coordinated reception

Synchronized tree formation within the connected components helps in spreading the synchronization within the connected component. By using coordinated reception the interference barriers between the connected components are broken which spreads the synchronization across the network. Each tree has a tree identifier (ID) and each BS joins the tree at a specific stratum level. As mentioned previously there are multiple trees in the network, however only one tree is synchronized to the external clock and the other non-synchronized trees have BSs that are multi-hop synchronized with each other but not to the external clock. Each tree has a root with stratum ID 0. Stratum ID 0 also indicates that the stratum level is 0. In the synchronized tree the root BS is directly synchronized to the external clock and has both tree and stratum IDs 0. BSs that are directly synchronized with the root BS have stratum ID 1, and so on. A BS starts transmitting synchronization signals once it has a tree ID and stratum ID and it continues to serve its own UEs. The tree and stratum IDs may be encoded with the synchronization signal.

3.4.1 Synchronization state update protocol

The synchronization state of a BS indicates whether the BS has acquired external clock timing or not. Each BS can be in either of the following synchronization states *viz.* synchronized tree, non-synchronized tree. Each synchronization state has a specific tree ID. Each BS asynchronously and periodically updates its synchronization state as given below

- *Broadcast synchronization signal:* Each BS j broadcasts a tree ID t_j and a stratum ID s_j.

- *Selecting synchronization candidate:* Synchronize to the BS with the lowest tree ID t_c and lowest stratum ID s_c. If there are multiple such BSs, then the BS with the highest SINR is chosen. Tree ID of the acting BS becomes $t_j = t_c$, stratum ID becomes $s_j = s_c + 1$. If the acting BS does not hear any other BSs, then it forms its own tree with a random tree ID other than 0, and takes the stratum ID $s_j = 0$ (root).

3.4.2 Protocol details

The protocol works in a distributed manner, except the centralized decision on selecting the root node of synchronized tree ID 0. It is assumed that the update times of each BS are different i.e. the algorithm is asynchronous. A BS that is switched on, starts with tree ID $t_j = \infty$ and stratum ID $s_j = \infty$, but does not initially broadcast anything. At a suitable time, it starts operating by performing a synchronization state update as mentioned in section 3.4.1. As the tree ID selection done by the root BS in a non-synchronized tree is random, distributed and from a limited tree ID space, there may exist the problem of tree ID collisions, which can be solved with special rules and is out side the scope of this research work.

A BS may receive synchronization signals from multiple neighboring BSs. In such a scenario, as it's desirable to minimize synchronization clock delays and propagation of synchronization errors, it is assumed that each BS will synchronize to the BS with the lowest available stratum ID. Reorganization can happen in a tree, when a BS either leaves the tree or joins to the tree. If any BS in a tree with ID $\neq 0$ hears a tree with a lower ID, he leaves without giving notice to his former tree. The members of the former tree are likely to hear member that left the tree, and join the new tree in subsequent iterations.

3.4.3 Synchronized tree creation

The root BS of a tree with ID 0 is assumed to be directly synchronized with the external clock. BSs which are able to receive the synchronization signals from the root BS start joining the tree in a multi-hop fashion. The ultimate goal is to form a local area femtocell network wide synchronized tree, which is synchronized to the external clock.

3.4.4 Non-synchronized tree creation

A BS which does not receive any synchronization signal from its neighbors, forms its own tree with a random tree ID other than 0, and takes the stratum ID $s_j = 0$(root). Such a tree is called as non-synchronized tree as it is not synchronized to the external clock. Neighboring BSs which are able to hear the synchronization signals from the root BS will join the tree in a multi-hop fashion. For any BS, the order of priority is to either join the synchronize spanning tree, or to join a non-synchronized spanning tree or to be a root BS and form a non-synchronized spanning tree.

3.4.5 Coordinated reception in a non-synchronized tree

Coordinated reception is implemented in a non-synchronized spanning tree with tree ID $\neq 0$. With the help of inter-BS signaling, the set of BSs within the non-synchronized tree align their measurement gaps in order to listen to synchronization signals from the synchronized tree or non-synchronized trees with a lower tree ID. Coordinated reception helps in removing the interference barriers which exist between the connected components and thereby reducing the number of connected components in the network. The presence of a single connected component in the network suggests complete network synchronization.

4 Testbed implementation

Proof of concept implementation of a simple network time synchronization scheme is implemented by using SDR. The objective of implementing the testbed was of two folds. First to implement TDD link synchronization between a TD-LTE BS and UE and then to implement a simple network time synchronization scheme using three BSs. The testbed is made up of multiple SDRs which emulates TD-LTE base stations and UEs. The TD-LTE BSs try to achieve network time synchronization by using network listening based on OTA measurements.

The main motivation behind implementing a real time test bed is to understand the dynamics of implementing the synchronization techniques on a real time basis. Unlike system level simulations, hardware implementations reflect the not so perfect world around us. For example, it is difficult to model the hardware limitations of the transmitter/receiver in simulations, whereas hardware implementation will shed light on all practical difficulties which deteriorate the signal quality. Also, the channel effects can be better understood in a hardware implementation. In this chapter an overview of the SDR implementation is provided and the test setup for implementing TDD link synchronization and network time synchronization is explained.

4.1 Software defined radios

The term "software defined radio" was first coined by Joseph Mitola III [30]. The main idea behind SDRs is to reduce the complexity of the radio at the hardware level and to make it a flexible radio device with the help of software. In SDRs, implementation of the baseband processing algorithms are carried out in the software level and the radio hardware is used only for the purpose of RF transmission and reception. Implementing the baseband processing at the software level gives SDRs the flexibility to be morphed into different types of radios with little or no change to the hardware. This means that the SDR can be used as a Frequency Modulation (FM) radio and by changing the software the same radio can be converted into a cellular BS.

To harness the full power of DSP algorithms the analog signals should be converted into digital domain and this is made possible by the use of ADC and DAC. Both ADC and DAC are part of the SDR hardware. There are different vendors who provide the hardware required for SDRs at an affordable price. USRP shown in Figure 16 is one such device which is manufactured by Ettus Research and its parent company National Instruments. USRP device acts as front end device which transmits and receives radio signals which are processed in the host computer. The data from the USRP is sent to the host computer with the help of USRP Hardware Driver(UHD). Application Programming Interface (API) is provided in order to access the UHD, which inturn controls the RF transceiver at the USRP. C++ programming language is used to communicate to the UHD.

A simple overview of the SDR implementation is given in Figure 17. A host computer is used to carry out the algorithms for baseband processing and the resulting

Figure 16: USRP device.

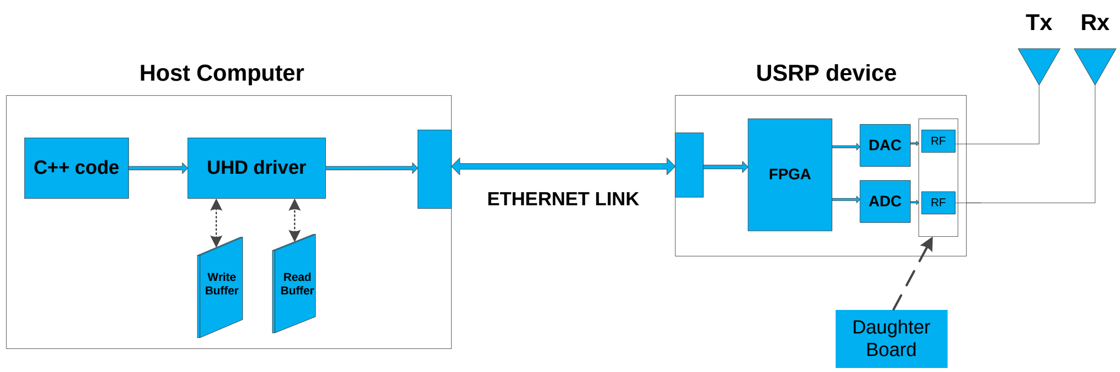

Figure 17: SDR implementation overview.

data is passed onto the USRP using the UHD. The host computer is connected to the USRP device by using an Ethernet Link. The USRP device has three major components the Field Programmable Gate Array (FPGA) chip, ADC and DAC converters and the daughterboard. The FPGA holds the digital down converters and Cascaded Integrator Comb (CIC) filters. The ADC and DAC is used for converting the signal from analog to digital domain and vice-versa. The daughterboard holds the RF transceivers which is used for translating the baseband signal into the carrier frequency. Different types of daughterboards are available and the appropriate one should be chosen based on the requirement.

4.2 Test setup

TDD link synchronization and network time synchronization are implemented in the testbed. Figure 18 gives an overview of network time synchronization and TDD link synchronization. The red dotted line in Figure 18 represents TDD link synchronization where the UE gets the timing information from the BS. This information is used to establish full duplex communication between them. The green line in Figure 18 indicates network time synchronization where the timing information is passed on from one BS to the other BSs.

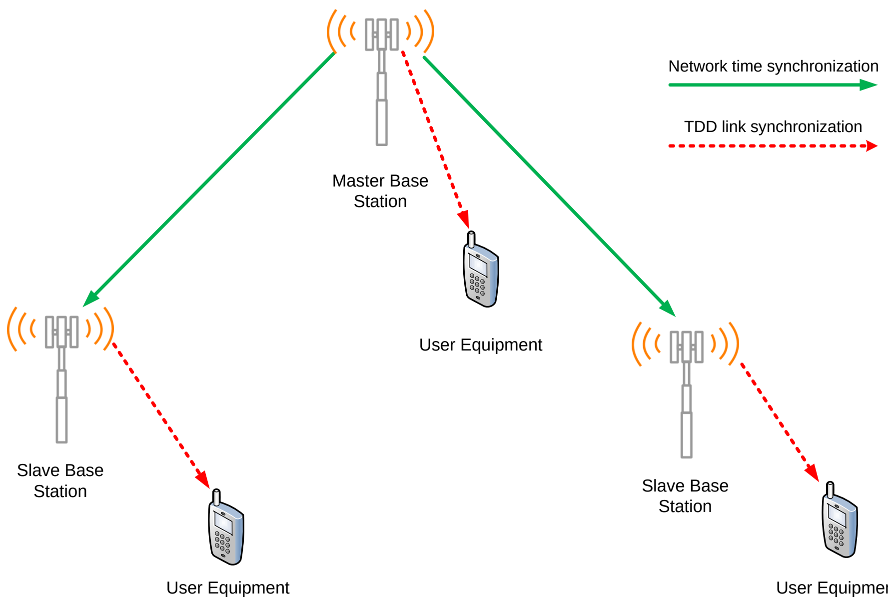

Figure 18: Network time synchronization and link synchronization in TD-LTE systems.

4.2.1 Transmitter chain

The transmitter chain is implemented based on the 3GPP LTE specifications [16]. The transmitter chain described here is based on LTE DL transmission. The block diagram of the transmitter chain transmitting TD-LTE frames is shown in Figure 19. N users are multiplexed using OFDMA and are mapped onto different RBs. Data from each user is encoded and modulated after which it is mapped into the corresponding RBs. After mapping all the users into the available RBs the IFFT operation is performed on the parallel input data. After attaching the CP to the IFFT output, the parallel data is converted into a serial stream of data and is sent to the USRP for transmission.

It is important to note that the pilot symbols used for channel estimation are sent at specific time-frequency instances along with the user data as per 3GPP specifications. It should also be noted that the reference symbol PSS is transmitted

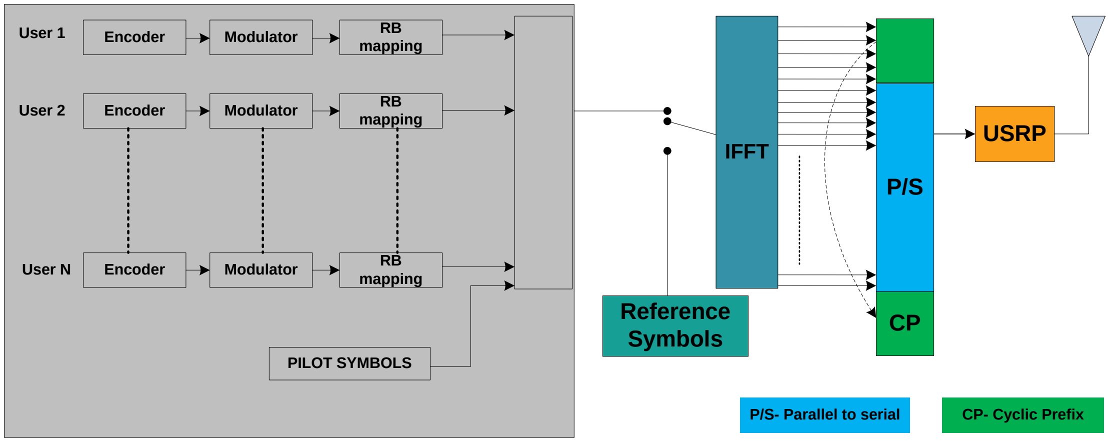

Figure 19: OFDM transmission using USRP.

in the third OFDM symbol of the special subframe and SSS is transmitted in the last OFDM symbol of subframe 0 and subframe 5. No user data is transmitted on the same subcarriers which are occupied by these reference symbols.

4.2.2 Receiver chain

The block diagram of the receiver chain is shown in Figure 20. Signal demodulation and detection happens in the receiver chain. The main emphasis in this chapter will be on deriving the OFDM symbol timing of the transmitted signal with the help of the PSS reference symbol and the correlator inside the synchronizer block shown in Figure 20. Since the location of the PSS reference symbol in the TD-LTE frame is known [16], the frame timing can be obtained from the symbol timing. The synchronizer block is made up of a correlator which is used for detecting the OFDM symbol timing. The symbol timing information is required to align the transmissions both in the case of link synchronization and network time synchronization.

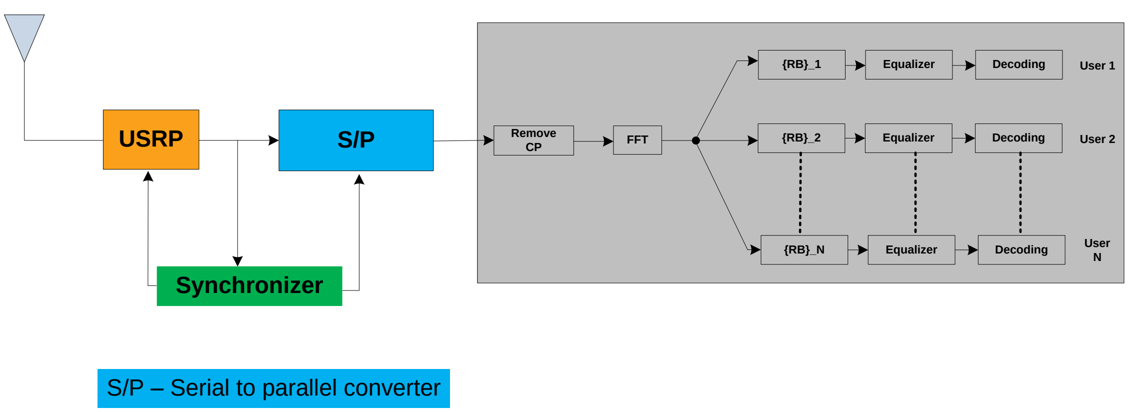

Figure 20: OFDM reception using USRP.

The correlation can either be done in time domain or frequency domain. Equation (4.1) gives the expression for correlation output in time domain using two discrete time domain complex sequences M and N. Equation (4.2) gives the expression for correlation output in time domian using two frequency domain complex sequences M and N.

$$r_{12}(j) = \frac{1}{N} \sum_{n=0}^{N-1} M(n+j) N^{*}(n) \tag{4.1}$$

$$r_{12}(j) = \frac{1}{N} F_{D}^{-1} [M(K) N^{*}(K)] \tag{4.2}$$

In equation (4.2), F_D^{-1} denotes IDFT. IDFT operation is implemented by the more efficient IFFT. The correlation window size in this testbed implementation is 1920 samples. The size 1920 corresponds to the size of one LTE subframe. The incoming sequence of sample size 1920 is correlated with conjugate of the PSS which is of length 128. The following discussion will highlight the computational efficiency of correlation in frequency domain.

If the correlation is done in time domain, the total number of computations required N_t is given by equation (4.3). The number of computations required N_f for correlation in frequency domain is given by (4.4). These equations were obtained from [31].

$$N_t = (M + N) \times N \tag{4.3}$$

$$N_f = L \log_2 L + L, \text{ where } L = \max(M, N) \tag{4.4}$$

In our case $M = 1920$ and $N = 128$. By plugging in these values into equations (4.3) and (4.4) it is found out that the correlation in time domain requires $N_t = 2,62,144$ complex calculations to calculate the output, whereas correlation in frequency domain requires approximately $N_f \approx 22861$ complex calculations. The computational effort is reduced by a factor $\frac{N_t}{N_f} \approx 12$. Thus frequency domain correlation turns out to be a more efficient and a faster method and hence it is useful in the case of real time correlation of received signals. FFT and IFFT operations are used to perform the correlation operation in frequency domain.

The output of the correlator is sent into a peak detector in order to get the symbol timing. The timing obtained from the peak detector is used to correctly decode the OFDM symbols. Synchronization accuracy is very important in order to correctly cut the CP and to extract the OFDM symbol. Synchronization update is also done periodically in order to overcome clock drift so as to maintain synchronization.

4.3 Implementation of TDD link synchronization

Link synchronization between the BS and UE is necessary to maintain the DL/UL switching time in TDD systems. In this testbed TDD link synchronization is established between a TD-LTE BS and UE. Two USRP boxes are used for this purpose. The test setup for TDD link synchronization is shown in Figure 21. The synchronization accuracy target is $\Delta t < 4.7\mu$s which comes from the CP duration. CP helps in preventing ISI which results from multipath components. Therefore the synchronization target should be less than the CP length in order to accommodate for prevention of ISI from multipath components.

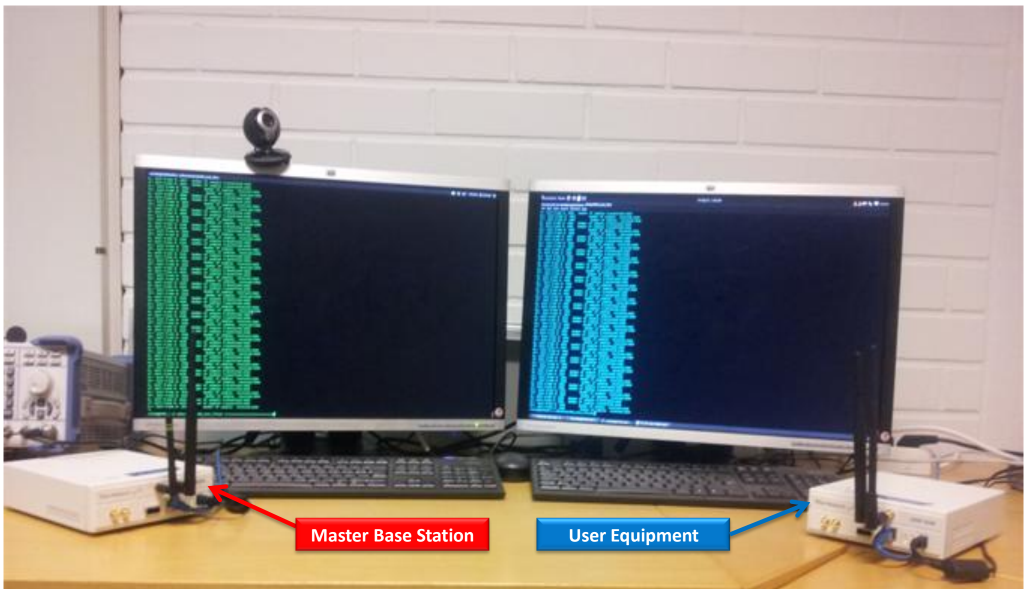

Figure 21: Test setup for TDD link synchronization.

The USRP box acting as the master BS transmits TD-LTE frames at a sample rate of 2M samples/sec. For this test setup TD-LTE frame with configuration 0 as shown in Figure 22 is used for transmission. The DL subframe will carry the user payload data and the special subframes contains the primary synchronization sequence in the third OFDM symbol which is used by the UE to detect the transmitted OFDM symbol timing.

DL	SP	UL	UL	UL	DL	SP	UL	UL	UL

Figure 22: TD-LTE frame configuration 0.

4.3.1 Establishing the TDD link synchronization

Figure 23 shows the DL and UL transmissions between a BS and a UE.

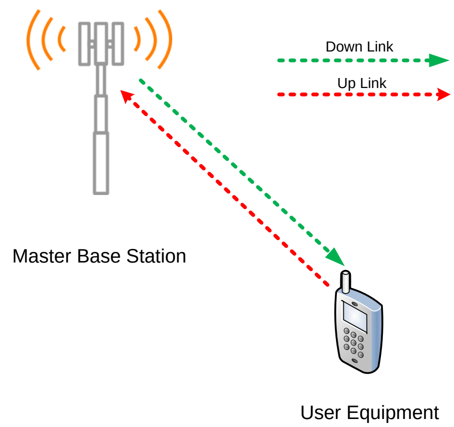

Figure 23: TDD link setup between a BS and UE.

The procedure for implementing TDD link synchronization is described below.

- The master BS starts its transmission at a predetermined frequency. TD-LTE frame with configuration 0 is transmitted by the master BS.

- It is assumed that the UE has apriori information about the master BS transmission frequency. With this information the UE listens to that particular channel for synchronization signals.

- The UE equipment performs correlation in frequency domain so as to detect the OFDM symbol start timing. When the UE detects the first peak, it tunes it own clock so as to transmit during the UL time slots as shown in Figure 24.

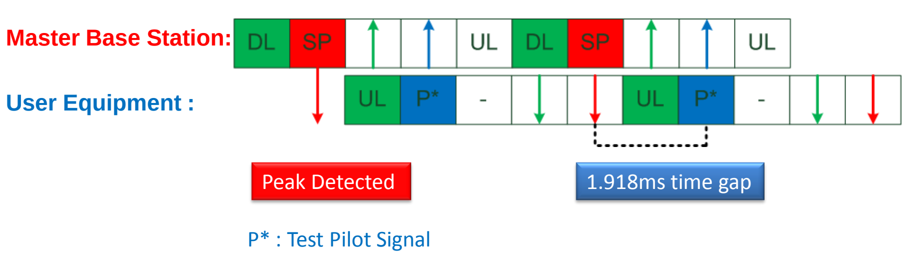

Figure 24: TDD link synchronization.

- It can be seen from Figure 24 that the UE transmits a test pilot signal P* in the UL direction. This test pilot is only used for the purpose measuring the synchronization accuracy and is not transmitted otherwise. Synchronization accuracy is measured by calculating the timing difference between the BS transmitted PSS sequence (red color in Figure 24) and the UE transmitted test pilot signal (blue color in Figure 24). If the timing difference between the BS transmitted PSS and UE transmitted pilot signal is equal to 1.918ms then it can be concluded that the synchronization accuracy between the BS and UE is 0. In other words there is no clock drift between the BS and UE.

- Inorder to verify the synchronization accuracy of the TDD link, the UE records both the DL and UL transmissions for post DSP.

4.4 Implementation of network time synchronization

The test setup for proof of concept implementation of a simple network time synchronization scheme using three TD-LTE BSs is described here. Three USRP boxes are used as TD-LTE BSs. The objective of this test setup is to align all the BSs to a common time scale as shown in Figure 25 and thus enabling network time synchronization. Hierarchical master-slave synchronization strategy is adopted here inorder to synchronize the three BSs. Therefore in this test setup we consider one master BS which acts as the root node and two other BSs take the role of slave nodes. The synchronization accuracy target in this case is $\Delta t \leq 4.7\mu s$ which comes from CP duration. Since there is a higher probability of having direct line of sight path for inter-BS link, effects of multi path components would be minimum. This justifies the choice of the synchronization accuracy target.

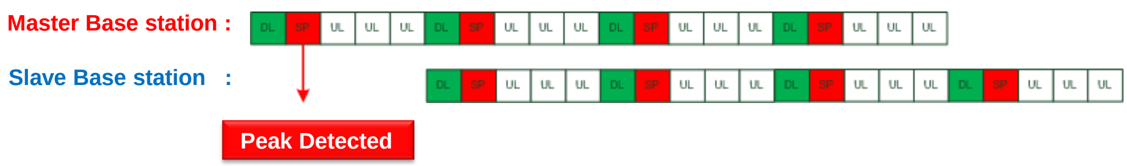

Figure 25: Network time synchronization by aligning time scales.

Identifiers (IDs) are required in this test setup to differentiate the BSs and their transmissions. The PSS with IDs $0, 1, 2$ are used for the purpose of identifying different BSs. Each BS transmits an unique PSS which is used as the BS-ID. There are two possibilities to establish a master-slave tree based network time synchronization for three BSs. The test for both these cases are discussed here.

The clocks of the slave BSs usually tend to drift away from its parent clock. For example, if slave BS 2 is connected to a master BS through another slave 1 BS as shown in Figure 27, then the clock of slave 2 BS might drift away faster from the master BS as it is connected to the master BS in a multi-hop fashion. Clock drift experienced at slave BS 2 will be the additive sum of clock drift between slave 1 BS-master BS and slave 1 BS-slave 2 BS. Therefore two different kind of test setups are implemented in the hardware to observe this behavior and to correct them.

Test setup 1 can be seen in Figure 26. In this setup the slave BSs are connected directly to the master BS. The clocks of the slave BS are tuned by listening to the master BS.

Test setup 2 is shown in Figure 27. In this setup the slave 1 BS is able to hear the synchronization signals from the master BS but the slave 2 BS does not hear the master BS. However, it is able to hear slave 1 BS and therefore joins it. In effect slave 2 BS also gets synchronized to the same time scale as the master BS, but in a multi-hop fashion.

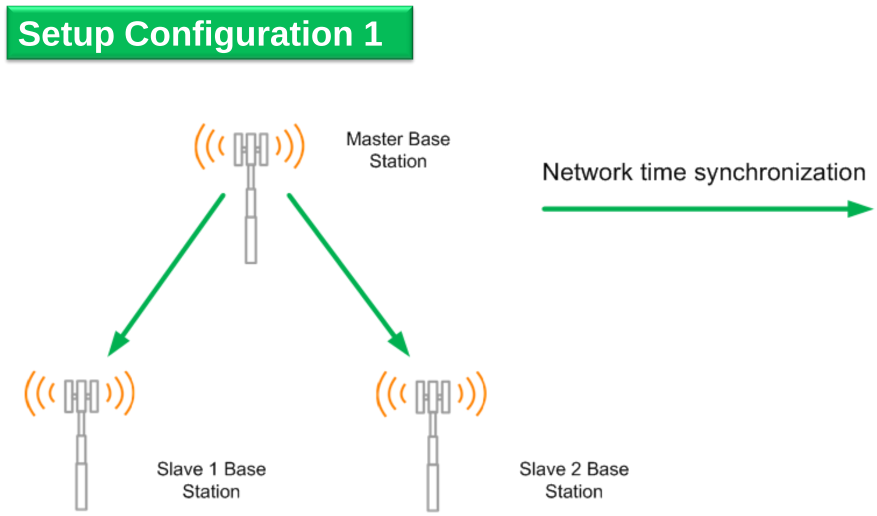

Figure 26: Tree based network time synchronization configuration 1.

4.4.1 Network time synchronization procedure

The procedure for implementing network time synchronization is described below. It is assumed that all the BSs have apriori information on the transmit carrier frequency and the all of them listen at the same carrier frequecny.

- The master BS start its transmissions. The master BS transmits with BS-ID 0 and hence transmits PSS 0.
- When a slave BS is turned on, it checks for synchronization sequences with BS-ID 0 and BS-ID 1. If a slave BS is able to hear both the synchronization sequence, it join the BS with the lowest ID. The priority is always to join the master BS.
- If the slave BS join BS-ID i, it will assume a BS-ID $i{+}1$ and will transmit PSS $i{+}1$. Note that the maximum available value of PSS ID is 2.
- After synchronization, it is observed that the clock of the slave BS will drift away with respect to its parent clock. In order to prevent clock drift, time update is performed.

4.4.2 Measurement gaps

The time update of the slave BSs are done with the help of measurement gaps. Measurement gaps are empty special subframe slots, during which the slave BS can listen to its parent BS, in order to update their clocks. In this test setup, one measurement gap per frame is used for updating the time as shown in Figure 28 and measurement gaps reappear after every 50 frames. The length of the measurement gap is 1920 samples, which is also the length of the special subframe. The measurements at

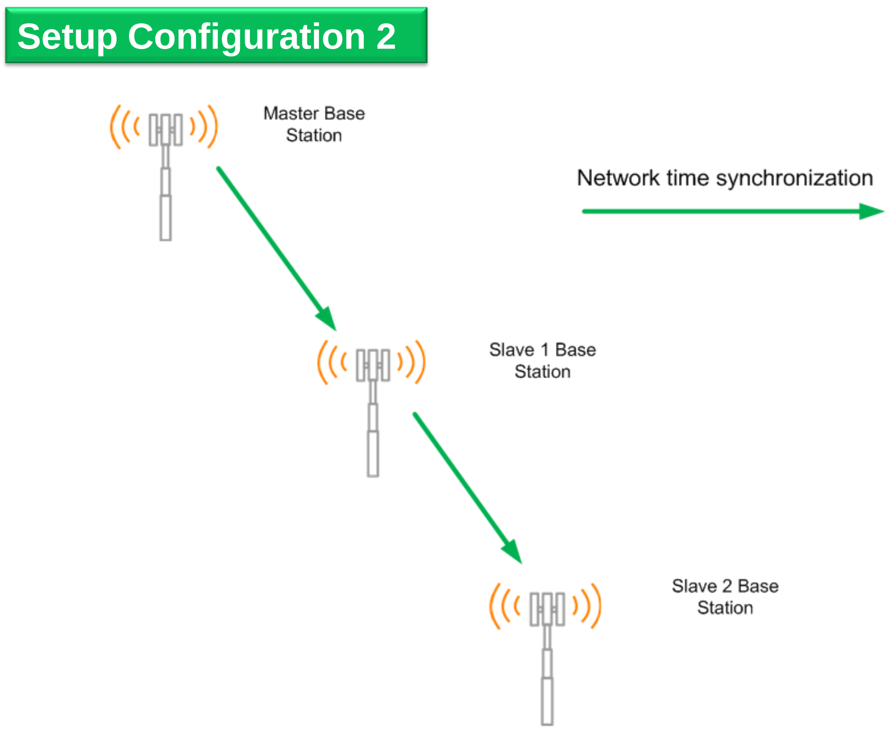

Figure 27: Tree based network time synchronization configuration 2.

the slave BS indicated that within the time duration of 50 frames after obtaining the initial synchronization, there was negligible clock drift. However, after every 50 frames the slave BSs tend to drift away from its parent clock by one or more samples. Therefore the measurement gaps were inserted after every 50 frames to remove the observed clock drift. In a three BS network scenario such as this testbed, since the slave BSs are turned on with a delay between them, the probability of measurement gaps overlapping is minimum.

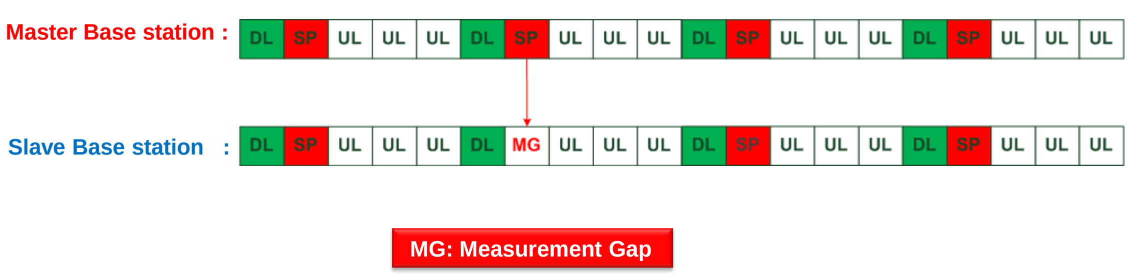

Figure 28: Measurement gap for time update.

5 Results and analysis

In this chapter the results of the research work carried out in chapter 3 and chapter 4 are presented and analyzed. Coordinated reception and transmission techniques are analyzed and investigated with the help of system level simulations. The selected method for simulations is monte carlo simulation. This particular method was chosen over analytical methods because monte carlo simulations provide a more realistic model of the system. SDR based implementation is used for the proof of concept implementation of network time synchronization in TD-LTE BSs.

5.1 Coordinated reception simulation results

Investigation of coordinated reception which reduces the interference experienced in network listening by coordinating the reception times of non-synchronous BSs was carried out in Chapter 3. In this section the simulation model is described and performance results of coordinated reception are analyzed. Figure 29 shows the modern office building which was considered for simulation. This modern office building is made up of multiple floors, large offices and corridors, as well as an atrium with glass inner walls and without floors. The motivation for investigating an office building with an atrium springs up from the fact that such a building design will cause heavier inter-BS interference thereby providing a more challenging environment for the self-organizing network studies. The system level assumptions are described in Table 3, which are based on a winner path loss model, except for the building shape [32]. 4 BSs and 20 UEs are dropped per floor in the office building. It is assumed that one of the randomly selected BS is synchronized with the external clock and remaining BSs try to synchronize using hierarchical master-slave approach, which is also the case in [7].

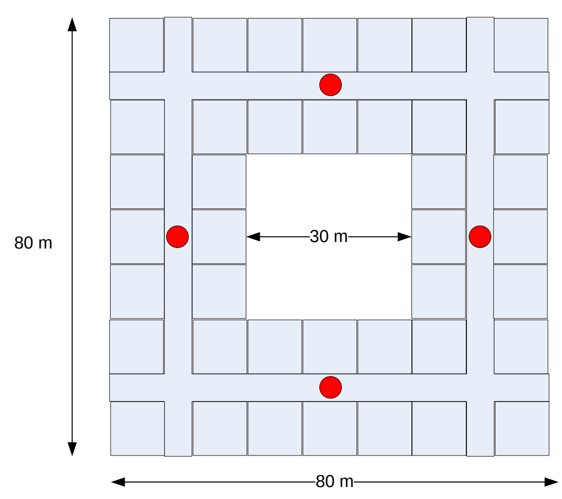

Figure 29: One floor layout of an office building with an atrium.

Table 3: System level simulation assumptions.

Number of Buildings	1
Building dimensions	80m * 80m
Number of floors	3,6,12
Room dimensions	10m * 10m
Corridor Width	5m
Room height	3m
BS height	2m
UE height	1m
Boundary conditions floor direction	wrap-around
Antenna patterns	Omni directional
carrier frequency	2.6 GHz
Line-of-sight	in same corridor
LOS path loss	A=18.7,B = 46.8,C = 20
Corridor-to-room path loss	A=36.8,B = 43.8,C = 20
Room-to-room path loss	A=20,B = 46.4,C = 20
Inner Wall loss	5 dB per wall
Outer Wall loss	14 dB per wall
Window loss	2 dB
Transmit Power P	24 dBm
Number of clock synch BSs per building	1
BSs per floor	4
UEs per floor	20
UE distribution	random per floor and room
Synch thresholds	-13, ... ,4dB
Load on shared & control channels	full
Number of Drops	1000

5.1.1 Comparison of network listening algorithms

Wireless network which uses network listening based multi-hop network time synchronization might be divided into multiple connected components as shown in Figure 15. The system which is modeled here consists of a single synchronized tree component which has a root BS connected to the external clock and several other non-synchronized tree components. Interference barriers limit the spread of synchronization from the synchronized tree to the other non-synchronized trees. The proposed coordinated reception is compared with the baseline network listening synchronization [6] and with existing techniques of coordinated transmissions [7].

Synchronization performance of various algorithms is measured in terms of the ratio of non-synchronized BSs, the mean number of hops(stratum levels) to the root BS and the mean number of connected components in the network for various synchronization thresholds. The number of hops to the root BS, which is synchronized to an external clock, is reported only when atleast 75% of the BSs in the network are able to synchronize. The mean number of connected components in the network is defined as the mean value of the sum of synchronized and non-synchronized trees. The goal of the algorithm is to converge the network from multiple connected components to a single connected component. The mean number of connected components in the case of network listening and fully orthogonal techniques is defined as the mean value of the sum of synchronized trees(is equal to one in this case) and total number of non-synchronized BSs. While in the case of coordinated silencing and coordinated silencing with fully orthogonal, the mean number of connected components in the network is defined as the mean value of the sum of synchronized and non-synchronized trees.

Synchronization performance of various techniques for 3-floor atrium office building is described here. Simulations were also done for 6 and 12 floor office buildings to get comparable results. Synchronization performance in terms of the ratio of non-synchronized BSs which are not synchronized to the external clock can be found in Figure 30. Figure 31 depicts the mean number of hops to the root node which has external timing reference. Figure 32 depicts the mean number of connected components in the network. Coordinated reception and coordinated reception with full orthogonal synchronization was compared with the baseline network listening synchronization and the existing techniques such as stratified, fully orthogonal and macro diversity synchronization techniques for various synchronization thresholds.

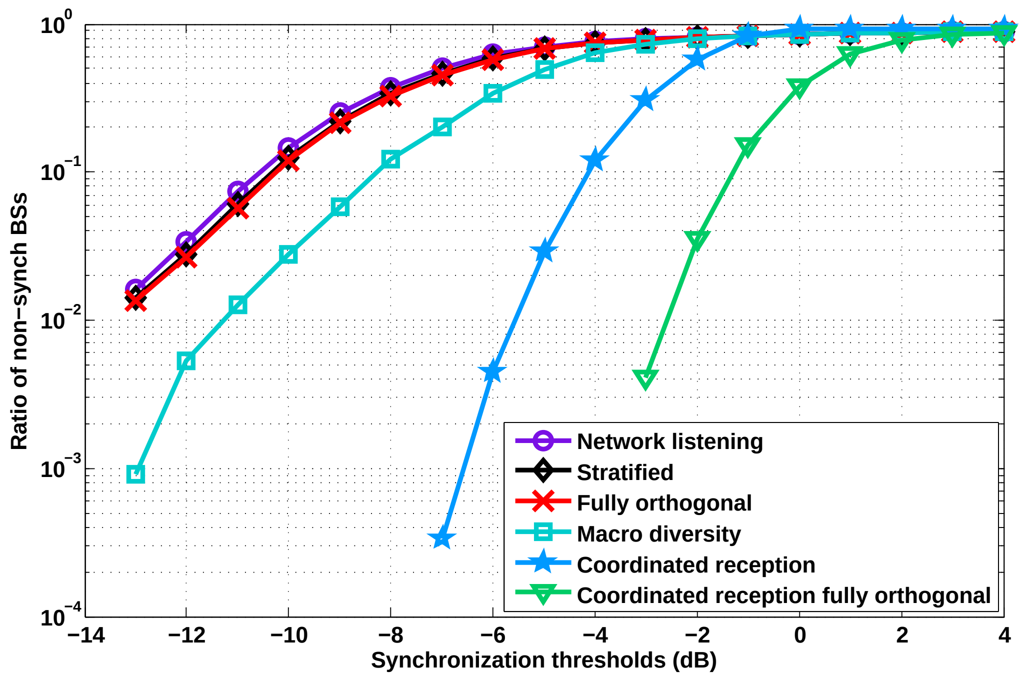

Figure 30: Ratio of BSs which are not able to multi-hop synchronize.

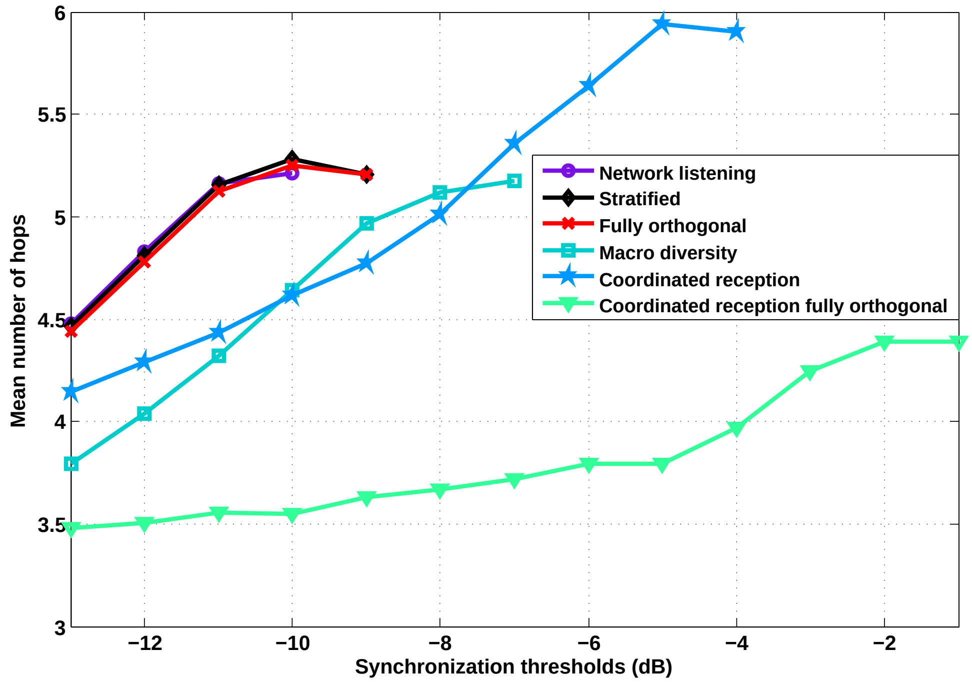

Figure 31: Mean number of hops to the external clock.

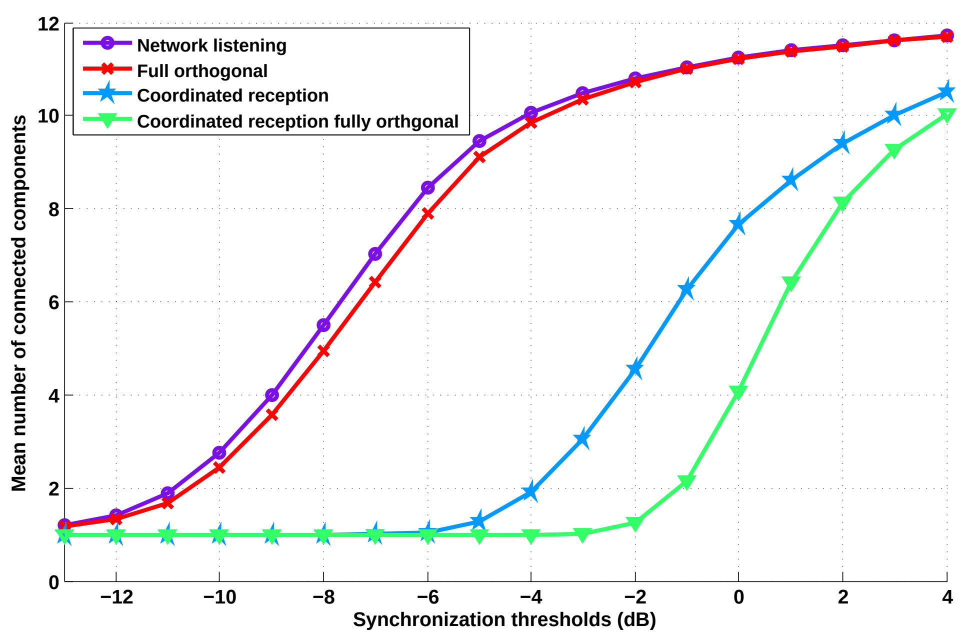

Figure 32: Mean number of connected components in a network.

From Figure 30 and Figure 32, it can be seen that the number of non-synchronized BSs and number of connected components increases with the increase in synchronization thresholds. In other words, when the synchronization threshold is high, average number of audible neighbors per BS is significantly lower than with a lower threshold. Synchronization signals are not able to overcome the interference barriers between the connected components, and therefore the network will not be completely synchronized. Coordinated reception outperforms both the baseline network listening synchronization and existing coordinated transmission techniques with least number of non-synchronized BSs, hop count and number of connected components as seen in Figures 30,31,32 respectively. Better performance of the coordinated reception compared to that of coordinated transmission can be attributed to the fact that coordinated reception removes the more dominant nearby interference sources and hence weakens the interference barriers between the connected components.

In both coordinated reception and coordinated reception with fully orthogonal, the network is able to converge into a single connected component as long as the synchronization thresholds are maintained within -7 dB and -4 dB respectively. On the contrary, existing synchronization techniques have a non-synchronized network with mean number of connected components close to 9 at these thresholds. The network is completely synchronized in the case of coordinated reception even at a 8dB higher synchronization threshold as compared to network listening approach. From the above results, it can be concluded that the proposed coordinated reception approach reduces considerable amount of interference from the neighboring BSs and thus helps in achieving complete network time synchronization in small cell wireless networks.

5.2 Measurement results

In this section, the measurement results of establishing the TDD link synchronization and Network time synchronization in the testbed are discussed and analyzed.

5.2.1 TDD link synchronization

TDD link is established between the BS and a UE as mentioned in section 4.3.1. The TDD link can be observed by using a third USRP box to sniff the spectrum. The result of sniffing the spectrum is shown by the time domain Figure 33. The blue and green overlapping waveforms indicate the Inphase and Quadrature components of the signal. The duplex arrangement is clearly visible in the Figure 33. The UE transmits a pilot sequence as shown in Figure 24. The purpose of the pilot sequence is explained in section 4.3.1. The timing between the BS transmitted PSS sequence and the UE transmitted pilot sequence is used to check for synchronization accuracy. In order to measure the synchronization accuracy of the TDD link the UE is made to record both the UL and DL transmissions.

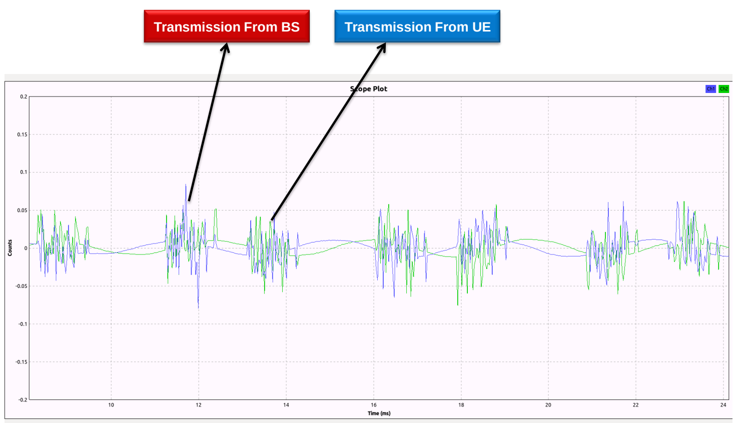

Figure 33: TDD transmission time domain waveform.

Table 4: Testbed Operational parameters.

Number of BS	1
Number of UE	1
LTE Transmission Bandwidth Configuration	6
Maximum occupied bandwidth (MHz)	1.08
Sample rate	2×10^6 Samples/sec
Tx Gain	14 dB
Rx Gain	25 dB
Carrier Frequency	2.49 GHz
Correlation Window size	1920 Samples
Correlation sequence	PSS
FFT size for OFDM symbol Generation	128

The testbed operation parameters for TDD link synchronization is given in Table 4. Correlation operation is performed on the data recorded at the UE and peak detection is performed on the correlation output. Since there are two different pilot sequences in DL and UL, the location of these two sequences in the TD-LTE frame will be highlighted by the peak detection output. The timing difference between these two peaks are measured to determine the synchronization accuracy. If the timing difference between the BS transmitted PSS and UE transmitted pilot signal is equal to 1.918ms then it can be concluded that the synchronization accuracy between the BS and UE is 0 which indicates no clock drift.

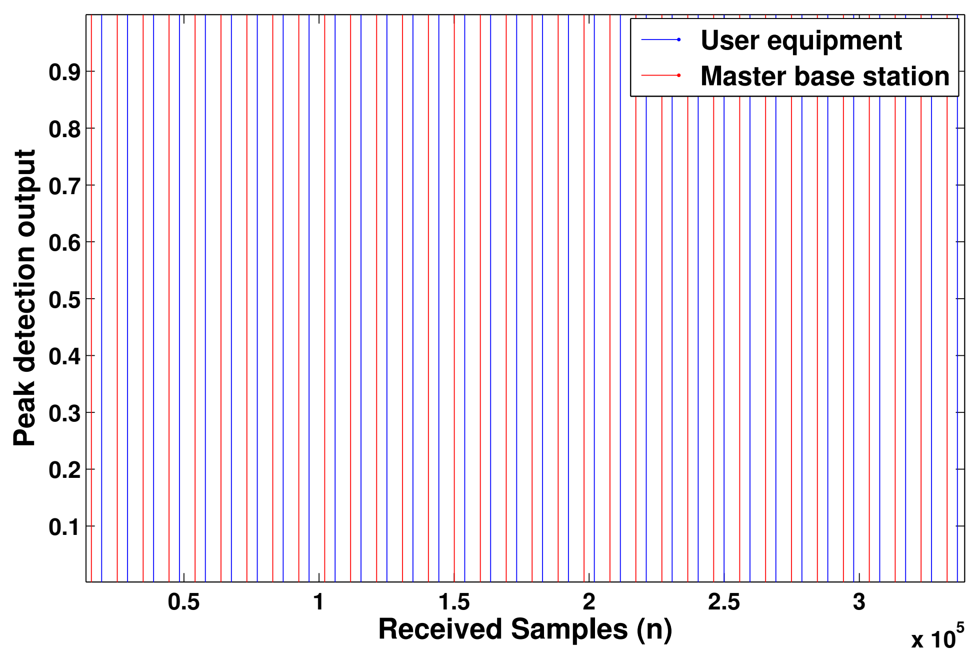

Figure 34: Peak detection output of the DL and UL data received at the UE.

From Figure 34 it can be seen that the synchronization accuracy between the Master BS and UE is almost constant. The PDF of the synchronization accuracy is plotted in Figure 35 and it can be seen that around 45% of the frames had no clock drift whereas around 50% of frame had 1 sample delay and a small percentage of frame had 2 samples delay.

5.2.2 Network time synchronization

The testbed operation parameter for network time synchronization is given in table 5. As mentioned in section 4.4.2, measurement gaps are used inorder to update the clock of the slave BS. Measurement results are taken from the more challenging setup configuration 2. Clock drifts are observed between the BSs as shown in Figure 36 and Figure 37. Figures 36 and Figure 37 show the severity of the clock drifts

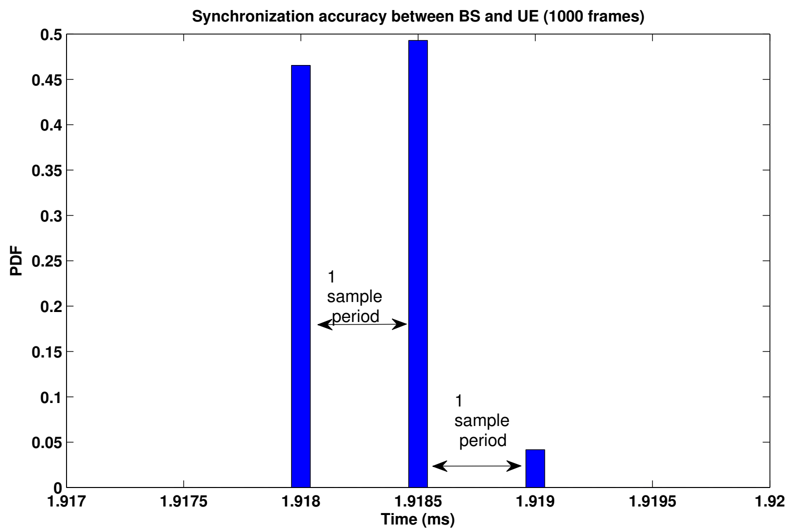

Figure 35: PDF of the synchronization accuracy.

between the BSs. If the clock drifts are not corrected it will result in reception of erroneous data at the receiver side.

In order to overcome the clock drifts time update is done with the help of measurement gaps. Figure 38 and Figure 39 show how clock drifts are controlled with the help of measurement Gaps. The corresponding PDFs of the clock drift between the BSs after time update is shown in Figure 40 and Figure 41. From Figure 42 and Figure 43 it can be observed that synchronization accuracy is well maintained with small clock drifts which are nullified with regular time updates.

Table 5: Testbed Operational parameters.

Number of BS	3
LTE Transmission Bandwidth Configuration	6
Maximum occupied bandwidth (MHz)	1.08
Sample rate	2×10^6 Samples/sec
Tx Gain	14 dB
Rx Gain	25 dB
Carrier Frequency	2.49 GHz
Correlation Window size	1920 Samples
Correlation sequences	PSS
FFT size for OFDM symbol Generation	128

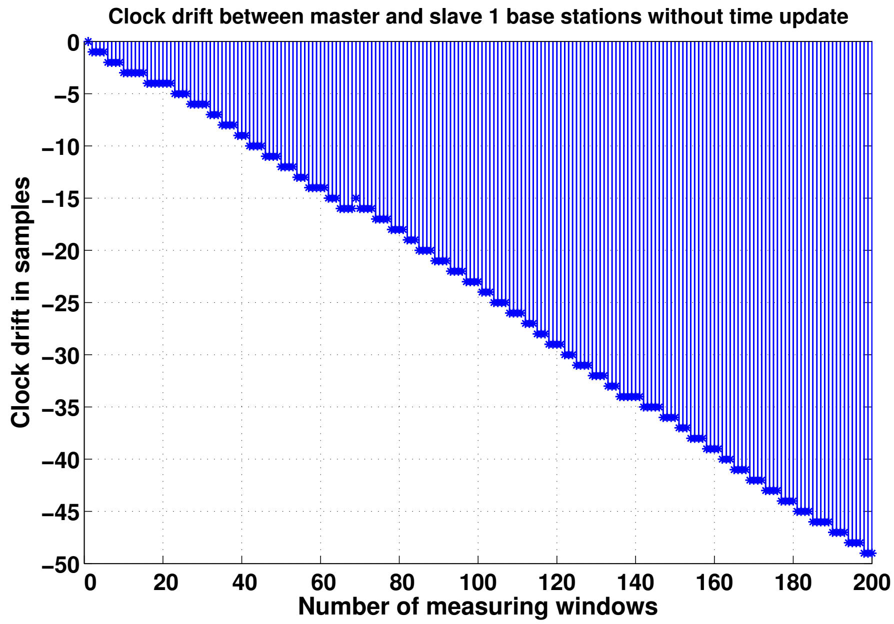

Figure 36: Clock drift between master and slave 1 BS without time update.

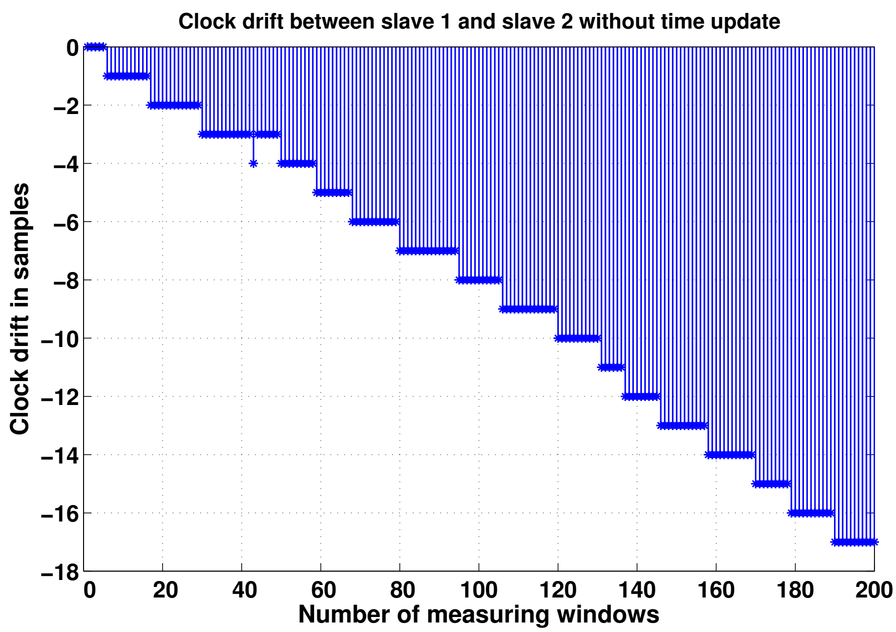

Figure 37: Clock drift between slave 1 and slave 2 BS without time update.

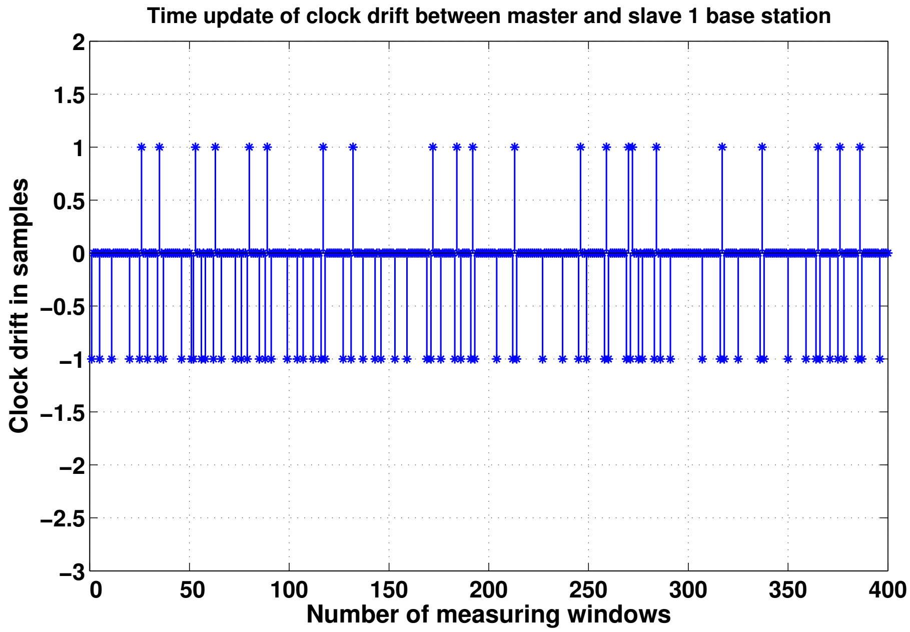

Figure 38: Clock drift between master BS and slave 1 BS with time update.

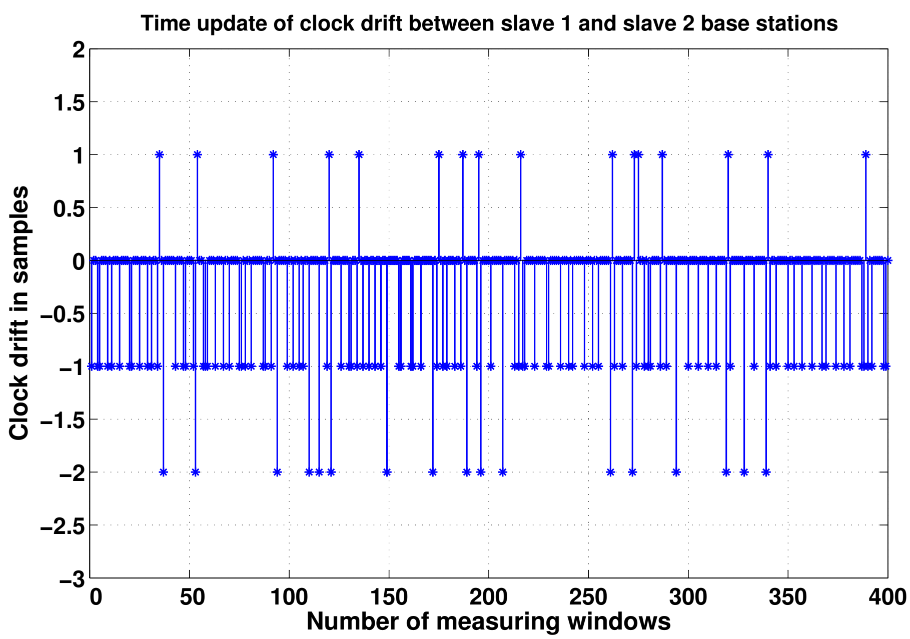

Figure 39: Clock drift between slave 1 and slave 2 BS with time update.

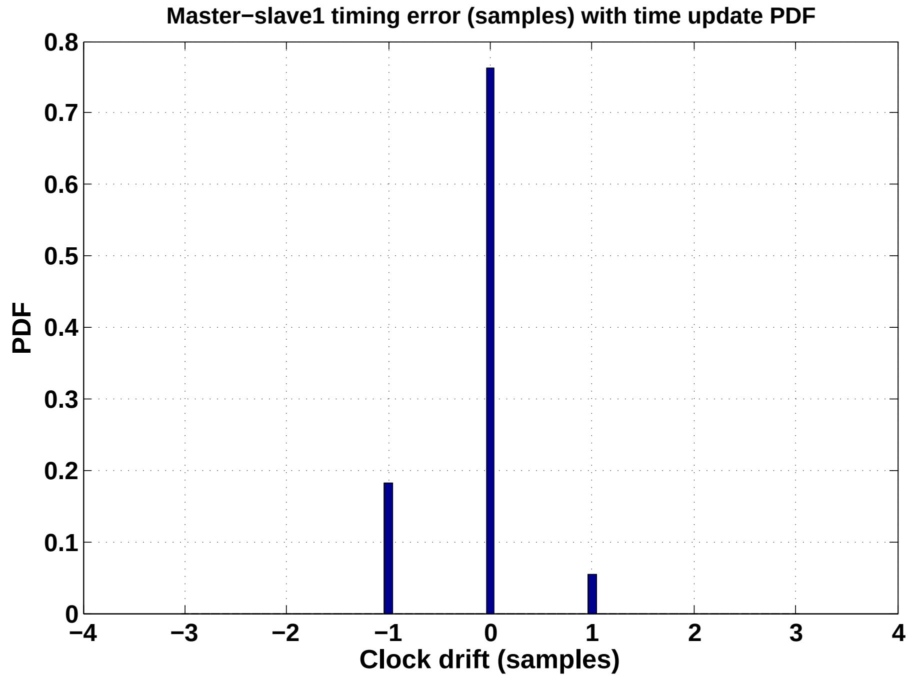

Figure 40: PDF of the timing error between the master BS and slave 1 with time update.

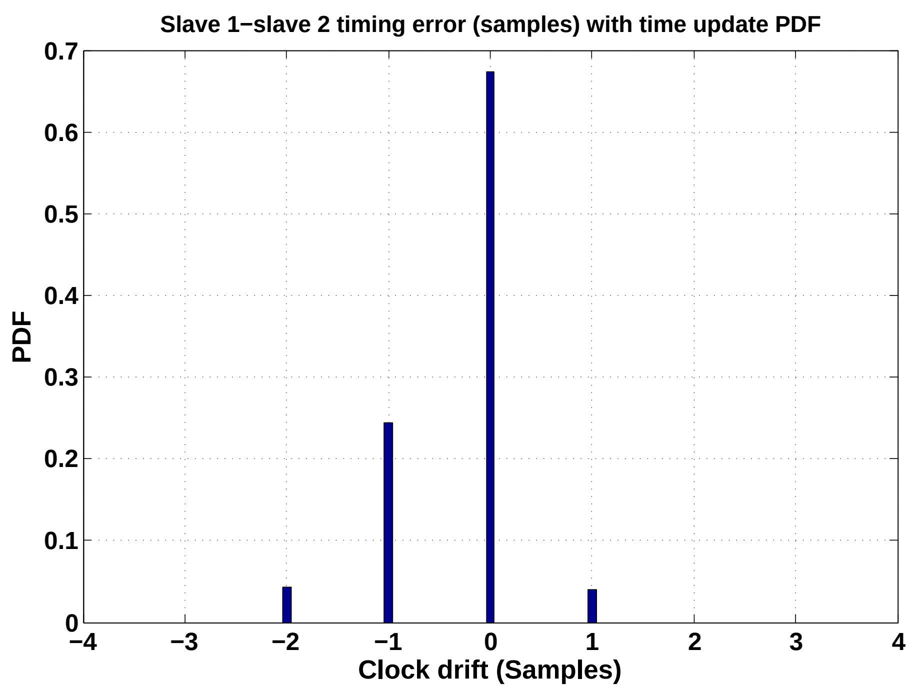

Figure 41: PDF of the timing error between the slave 1 and slave 2 with time update.

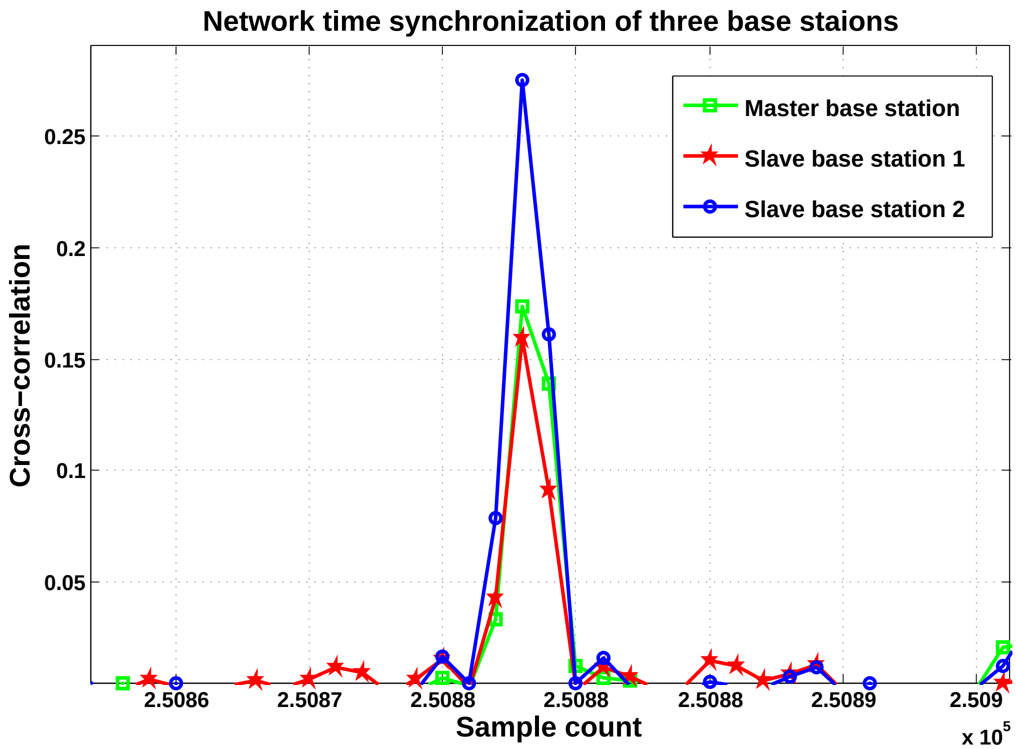

Figure 42: Perfect network time synchronization at a random instant.

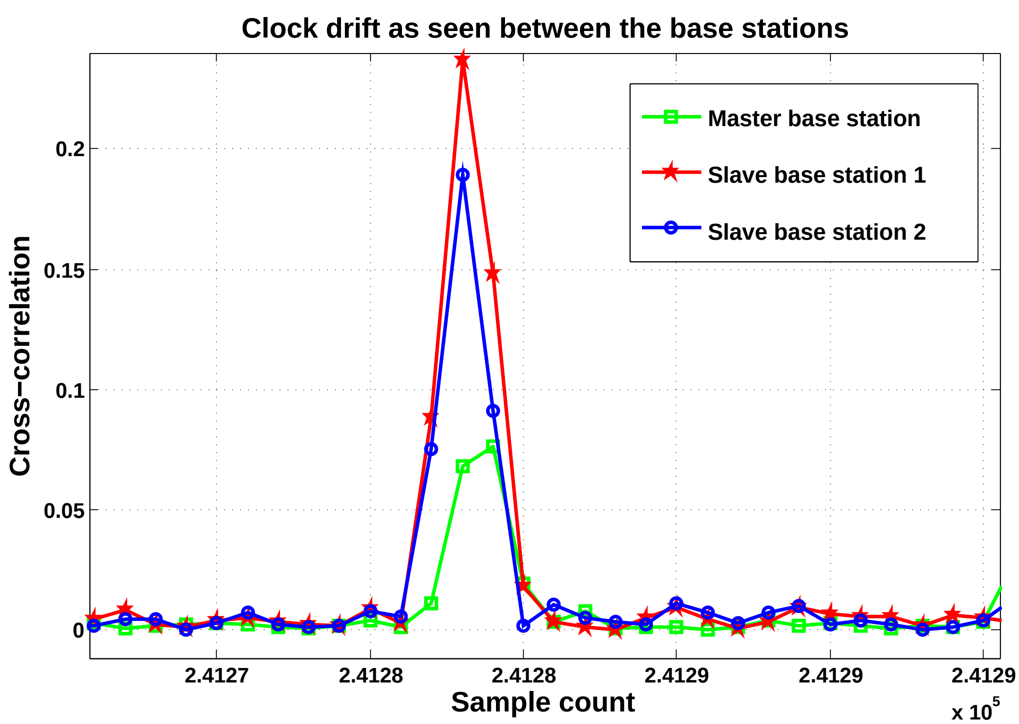

Figure 43: Network time synchronization with single sample drift at a random instant.

6 Conclusion and future work

Network listening is a synchronization technique used for wireless networks, where a BS is synchronized with another BS based on OTA measurements. This is a very useful technique for synchronizing TD-LTE femtocells as they suffer from poor indoor coverage of the GPS signals which provide them timing information. However network listening in femtocells suffers from interference coming from neighbor BSs which prevents the spreading of synchronization in the network. Coordinated reception tackles the problem of interference from the neighbor BSs. In coordinated reception the subsets of non-synchronous femto BSs cooperatively align their measurement gaps to simultaneously listen to synchronization signals from synchronized BSs. It was found that this approach of coordination among the subsets of non-synchronized BSs considerably reduces interference during network listening in a large femto cellular network. In an example network, it was found that the network is completely synchronized even at 8 dB higher synchronization threshold, with coordinated reception as compared to that of network listening synchronization.

A proof of concept implementation of a simple network time synchronization scheme was implemented using SDRs. USRP N200 boxes were used as SDRs. TDD link synchronization and network time synchronization were implemented using the SDRs. USRP N200 boxes emulated real time TD-LTE BSs transmitting TD-LTE frames. Configuration 0 of TD-LTE frame structure was used for the measurements. The PSS in the third OFDM symbol of the special subframe was used as the BS identifier. Correlation in frequency domain was found to be effective in deriving the timing when compared to correlation in time domain. From the testbed implementation of TDD link synchronization it was found that around 45% of the frames had no clock drift whereas around 50% of the frames had 1 sample delay and a small percentage of frames had 2 samples delay. Two different test setups were used to implement network time synchronization. It was found that after initial synchronization, the slave BSs tend to drift away from the timing of their parent BS. This clock drift was overcome by the use of measurement gaps. Measurement gaps are empty special subframe slots in which the slave BSs perform a timing update by listening to the synchronization signal from their parent BS. The measurement gaps are periodically repeated every 50 frames thereby maintaining tight synchronization between the master BS and its slave nodes.

The current hardware implementation provides an algorithm for synchronizing three BSs. In future this can be improved to support synchronization of multiple BSs. Also currently there is no mechanism to overcome node failures while maintaining synchronization. If a particular BS fails, then automatically all the BSs connected to this BS loose their timing information. The process by which these BS regain their synchronization by changing their parent node was not dealt with in this research work. This gives room for further development of the hardware implementation by making the network time synchronization scheme more robust to node failures. There were few practical limitations of this test bed setup. The clocks of the USRP boxes were not stable and some samples were lost from the read and write buffers due to buffer overflows.

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