PhD Dissertation

Synchronization of Cooperative Diversity Orthogonal Frequency Division Multiplexing System in Wireless Channel

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2013

ABSTRACT

Future wireless communication systems are required to provide services to mobile users for a variety of high data rate multimedia applications like VoIP, interactive gaming, video conferencing and web browsing in a wider coverage area. To support such diverse user requirements, a communication system must meet the following minimum criteria namely high data transfer rate, support for mobility, reliability and wider coverage area. In this work, the enabling technologies that have the potential to meet the requirements of future communication system either implemented individually or in unison with others are identified. Further, Synchronization is identified as a major challenge to robust and cost effective implementation and deployment of these technologies. Finally, synchronization algorithms are proposed for a variety of such technologies and their performance is evaluated using simulations and compared with other published algorithms.

OFDM is identified as pivotal technology for future wireless communication systems due to its robustness in dispersive wireless channel with a comparatively lower design and implementation complexity. However, OFDM alone cannot provide for enhanced throughput, reliability and coverage area especially in a time variant channel. In this work, OFDM is complemented with other technologies like MIMO, STBC, OFDMA and cooperative diversity. OFDM can be combined with these technologies in a number of ways depending on desired requirements in terms of throughput, reliability, mobility and coverage. The

OFDM combo considered in this work is referred as Cooperative Diversity Orthogonal Frequency Division Multiplexing (CD-OFDM) system.

A lot of research work has already been done regarding synchronization of OFDM but this work is unique because an effort is made to contribute synchronization algorithms for a scenario where OFDM is combined with other technologies.

The contributions made by this work include a preamble for CD-OFDM system and three variants of coarse timing synchronizer. Further, a low complexity carrier frequency offset estimator and compensator is proposed which is also applicable to OFDMA uplink scenario. A frame structure and protocol for implementing this CFO estimator is also presented. Finally, a channel estimation based fine timing synchronization mechanism is devised for CD-OFDM system. The performance of all proposed algorithms is evaluated using Monte Carlo simulations and results are found comparatively better than reference algorithms.

ACKNOWLEDGMENTS

First, I would like to extend my gratitude to my advisor Professor, Dr Shoab Ahmed Khan who has supported me in many ways throughout my PhD studies. It was really a privilege to work with him. He has been a great mentor and provided invaluable guidance and support.

I am also indebted to Professor, Dr Younas Javed for agreeing to be on my graduate examination committee (GEC) despite his official commitments. He was a constant source of encouragement and advice.

I would also take this opportunity to thank Dr Ali Hassan, GEC member, for his valuable suggestions that helped a lot in my research work. Further, his motivation and encouragement was a ray of light in desperate times during this endeavor.

I would also like to acknowledge the support that I received from Dr Muhammad Fasih uddin Butt, GEC member (external) for his insightful comments and valuable guidance.

I am obliged to all faculty members who contributed in my academic growth and made this accomplishment possible.

I would like to thank my colleagues for their relentless support and cooperation. Especially Aaqib Pervaiz and Asad Waqar Malik who were peers and well-wishers in thick and thin.

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GLOSSARY OF NOTATIONS

$j \overset{\text{def}}{=}$	Imaginary unit
$a \overset{\text{def}}{=}$	Scalar
$conj\{\, a\} \overset{\text{def}}{=}$	Complex conjugate of a scalar a
$\lvert a \rvert \overset{\text{def}}{=}$	Magnitude of a
$\boldsymbol{a} \overset{\text{def}}{=}$	Vector
$\boldsymbol{a}^{\boldsymbol{T}} \overset{\text{def}}{=}$	Transpose of a vector $\boldsymbol{a}$
$conj\{\, \boldsymbol{a}\} \overset{\text{def}}{=}$	Complex conjugate of a vector $\boldsymbol{a}$
AF	Amplify and forward relay protocol
ACK	Acknowledgment
ARQ	Automatic Retransmission Request
ADSL	Asymmetric Digital Subscriber Line
AOA	Angle of arrival
$\lfloor\ \ \rfloor$	Floor
$\lceil\ \ \rceil$	Ceiling
BN	Base Node
CIR	Channel Impulse Response
CTF	Channel Transfer Function
CP	Cyclic Prefix
CN	Cooperating Node
CFO	Carrier Frequency Offset

CSI	Channel State Information
CD-OFDM	Cooperative Diversity OFDM system
C-phase	Cooperation phase
DN	Destination Node
$\delta(t) \stackrel{\text{def}}{=}$	$\begin{cases} 1 & t = 0 \\ 0 & otherwise \end{cases}$
DnF	Decode and forward relay protocol
$d_{fine,adv} \stackrel{\text{def}}{=}$	Fine timing pre-advance
DSSS	Direct-Sequence Spread Spectrum
DMT	Discrete Multi-Tone
DVB-T	Digital Video Broadcasting For Terrestrial Television
DVB-H	Digital Video Broadcasting For Handheld Terminals
ESPIRIT	Estimation Of Signal Parameters Via Rotational Invariance
ECM	Expectation Conditional Maximization
$E[n] \stackrel{\text{def}}{=}$	Statistical expectation
FD	Frequency Domain
FCS	Frame Check Sum
FDCP	FD Cooperation Preamble
FDBP	FD Broadcast Preamble
FEC	Forward Error Correction
FFT	Fast Fourier Transform
FHSS	Frequency-Hopping Spread Spectrum
$G_{x,y} \stackrel{\text{def}}{=}$	Geometric gain from node x to node y

$\gamma_{th,fine} \stackrel{\text{def}}{=}$	Fine timing threshold
HARQ	Hybrid Automatic Repeat Request
HDSL	High-bit-rate Digital Subscriber Line
$\Im\{a\} \stackrel{\text{def}}{=}$	Imaginary part of a complex scalar a
IFFT	Inverse Fast Fourier Transform
ISI	Inter Symbol Interference
ICI	Inter Carrier Interference
LTE	Long Term Evolution
LS	Least-Squares estimation
$L_{pre} \stackrel{\text{def}}{=}$	Number of repetitive patterns used in a preamble frame
$\Pi(\frac{t}{T}) \stackrel{\text{def}}{=}$	$\begin{cases} 1 & \lvert t\rvert \leq T \\ 0 & otherwise \end{cases}$
ML	Maximum Likelihood
MAI	Multiple Access Interference
MIMO	Multiple Input Multiple Output
MCDS	Maximum Channel Delay Spread
MUSIC	Multiple Signal Classification
$N \stackrel{\text{def}}{=}$	FFT size of an OFDM system
$N_u \stackrel{\text{def}}{=}$	Number of useful subcarriers in OFDM excluding virtual subcarriers
$N_G \stackrel{\text{def}}{=}$	Number of subcarriers used for Cyclic prefix
$N_c \stackrel{\text{def}}{=}$	$N + N_G$
$N_{pre} \stackrel{\text{def}}{=}$	Number of OFDM symbols used for preamble frame

NAK	No-acknowledgement
NLOS	Non-Line-of-Sight coverage
NMSE	Normalized Mean Square Error
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
PAPR	Peak-To-Average Power Ratio
PLL	Phase Lock Loop
RN	Relay Node
$\Re\{a\} \stackrel{\text{def}}{=}$	Real part of a complex scalar a
ρ_{max}	Maximum two-way propagation delay
STBC	Space Time Block Coding
STTC	Space-Time Trellis Codes
SFN	Single Frequency Networks
SN	Source Node
SM	Spatial Multiplexing
SAGE	Space Alternating Generalized Expectation Maximization
CAS	Carrier Assignment Schemes
$sinc(t) \stackrel{\text{def}}{=}$	$\frac{\sin(\pi t)}{\pi t}$
$T \stackrel{\text{def}}{=}$	Time duration of all subcarriers in OFDM excluding CP
$T_u \stackrel{\text{def}}{=}$	Time duration of useful subcarriers in OFDM excluding virtual subcarriers
$T_G \stackrel{\text{def}}{=}$	Time duration of subcarriers used for Cyclic prefix

$T_c \stackrel{\text{def}}{=}$	$T + T_G$
$\tau_{max} \stackrel{\text{def}}{=}$	Maximum channel delay spread
TO	Timing Offset
TD	Time Domain
$u(n) \stackrel{\text{def}}{=}$	Unit step function
UN	User node
VDSL	Very-high-speed Digital Subscriber Line
V-BLAST	Vertical Bell Laboratories Layered Space Time
WiMAX	Worldwide Interoperability for Microwave Access
WSS	Wide sense stationary process
WATM	Wireless asynchronous transfer mode
$x(t) \stackrel{\text{def}}{=}$	Time continuous signal
$x[n] \stackrel{\text{def}}{=}$	Discrete signal

CHAPTER 1

INTRODUCTION

1.1 MOTIVATION

Most of the inventions in the human history were made possible by constantly evolving and increasingly demanding life style of human race. As always, even today research effort is overwhelmingly directed towards development of technologies that are likely to support our agile and mobile life style. The telecommunications industry is no exception to this rule and lot of research is being done to develop technologies that can support high data rate transfer on the move. Future wireless communication systems are required to provide services to mobile users for a variety of high data rate multimedia applications like VoIP, interactive gaming, video conferencing and web browsing in a wider coverage area [1]. To support such diverse user requirements, a communication system must meet the following minimum criteria namely high data transfer rate, support for mobility, reliability and wider coverage area.

In an orderly fashion, this thesis first identifies a “problem area” and subsequently moves toward its solution in interlinked steps. In this dissertation, firstly, the enabling technologies that have the potential to meet the future-communication-system requirements (implemented either individually or in unison with others) are described. Further, Synchronization is identified as a major challenge to robust and cost effective implementation and deployment of these technologies. Most importantly, in this work, an effort is made to look at the synchronization issue as a cross-technology problem and to design wide range of synchronization algorithms encompassing these technologies.

As far as the data rate and reliability is concerned, wired communication systems using optical fiber are upto the task but falters on the mobility issue. The mobility issue totally changes the scenario because it forces system designers to shift from benign wired channel to treacherous wireless channel. From throughput perspective, it is encouraging that wireless communications has evolved over the years from narrowband systems to high-data-rate broadband systems. However, it is very challenging to sustain a high data rate transmission in a frequency selective and dispersive wireless channel.

The main problem with high data rate single carrier wireless systems is that as the data rate increases, the symbol duration shrinks and becomes smaller than the maximum channel delay spread (MCDS) thus making the channel frequency selective. Putting it in another way, symbol rate of a system must be less than coherence BW of the channel for avoiding frequency selective fading distortion. A frequency selective channel results in severe inter-symbol-interference (ISI) and irreducible BER. For an ISI free system, its transmission rate is upper-bounded by coherence time. The data rate in FDMA and GSM systems is limited primarily due to this reason.

There are many ways to mitigate the effects of frequency selective channel including equalization, spread spectrum and OFDM but each has its pros and cons. Equalization can mitigate channel induced ISI but its complexity increases manifold with increase in channel taps. Direct sequence spread spectrum (DSSS) can mitigate ISI due to its inherent ability to suppress multipath interference by using code-correlation or RAKE receiver. However, RAKE receiver uses separate correlator for each arriving multipath that renders it computationally complex and expensive to implement. On the other hand, Frequency Hopping Spread Spectrum (FHSS) avoids ISI by shifting carrier frequency to a new band before the arrival of multipath. Hop rate must be larger than or equal to the symbol rate for effective ISI mitigation in a frequency selective channel. On the down side, hopping makes receiver implementation somewhat complex and is not spectrally efficient.

OFDM uses a novel but simple idea to overcome this problem; it divides the signal band into many narrowband signals with larger symbol duration as compared to the actual signal. These low rate signals are transmitted simultaneously using orthogonal subcarriers. It makes the symbol duration larger than MCDS thus transforming a frequency selective channel into flat frequency channel without ISI. Yet another plus is that it is implemented using efficient FFT algorithm and single tap FD equalizers thus making overall receiver design simple and cost effective. Due to these reasons, OFDM is considered technically more suitable to provide high data rates in a frequency selective wireless channel as compared to other available options. OFDM is likely to be incorporated in IEEE 802.20a standard that will provide large data rate for highly mobile users. IEEE 802.11a LAN and IEEE802.16a MAN standards are already based on OFDM technology [2], [3], [4], and [5].

Simple OFDM can support substantially large data throughput by increasing the number of subcarriers but a more feasible solution is to lend a hand from other technologies. In line with this argument, to further increase the transmission rate, multiple transmit and receive antennas can be used to open up additional channels in spatial domain. The technology that incorporates this concept is called multiple input multiple output (MIMO) system. IEEE 802.11n WLAN and IEEE802.20 MAN standards are based on MIMO technology. A MIMO system can theoretically enhance the capacity for a flat fading channel by a factor equal to the minimum number of transmit or receive antenna. Due to these reasons, the combination of OFDM and MIMO is extensively used in numerous communication systems for supporting high data rate for mobile users [6], [7], [8], [9]. Theoretical studies have shown that MIMO–OFDM technology may result in highly bandwidth efficient systems to the extent of 10 bits/Hz.

The MIMO–OFDM combination has a major limitation that in most of the cases it is not feasible to use multiple antennas at the user end due to power, cost and size constraints [10]. The solution to this problem is the use of distributed antenna nodes that cooperate with each other to form a virtual antenna array in place of physical antennas thus providing spatial diversity and array gain. Spatial diversity can be effectively used to mitigate fading in a wireless channel. Such systems are known as "Cooperative Diversity (CD) Systems". Research has shown that benefits accruing from centralized MIMO systems are also attainable by using CD system. CD systems using relays can also be used to increase the coverage area. CD systems are widely used in relay, sensor and broadcast networks [11] [12] [13], [14]. Owing to these reasons, beyond-third generation and fourth-generation systems are likely to incorporate relay protocols like amplify-and-forward (AF) and decode-and-forward (DnF). Most recently, IEEE LAN/MAN standard 802.16j has incorporated relays [15].

In addition to frequency selectivity, another peril of mobile wireless channel is multipath fading. The relative motion of receiver and transmitter renders a radio channel time variant because propagation path changes. This time variant nature of mobile wireless channel results in a phenomenon that is conventionally categorized as slow fading and fast fading. It is pertinent to mention that if symbol duration is larger than the channel coherence time then result is a fast fading channel that introduces irreducible BER loss. BER performance suffers because fast fading distorts the baseband pulse shape thus impinging on the PLL and matched filter performance. Fading can be mitigated in many ways. First, fast fading can be avoided in OFDM by decreasing the symbol duration as compared to channel coherence time. Second, diversity can be used to make a channel less fading and it plays a vital role in adding reliability to a wireless communication system. However, an OFDM system practically denies harnessing any frequency diversity present in frequency selective channel by transforming it into a frequency flat channel. One way of adding diversity to an OFDM system is to design for spatial diversity. It is at times the preferred type of diversity because it does not incur any extra cost in terms of bandwidth and throughput. In an OFDM system, Space-time block coding (STBC) may provides spatial diversity without requiring CSI at transmitter side.

Finally, all communication systems less point-to-point and broadcast systems use one or other multiple access schemes like FDMA, TDMA and CDMA. Multiple access schemes are the hallmark of present day wireless communication system that enables the efficient use of RF bandwidth, a precious resource. OFDMA is a multiple access scheme that suits best in case of OFDM because it is carved out of the OFDM signal structure. OFDMA may also provide multi-user diversity by intelligent subcarrier allotment to different users based on their respective SNR.

The crux of preceding discussion is that future wireless communication systems are likely to be based on a mix and match of technologies like OFDM(A), MIMO, Cooperative Diversity and STBC.

1.2 PROBLEM STATEMENT

A wireless communication system built upon a harmonized mix of OFDM(A), MIMO, Cooperative Diversity and STBC technology is capable of supporting high-speed data transfer between mobile terminals. A space-time encoded cooperative diversity OFDM system (CD-OFDM) offers a number of benefits. First, OFDM makes it possible to design a simple receiver that uses low complexity frequency domain (FD) equalization to mitigate frequency selectivity by employing single multiplication per subcarrier. Second, cyclic prefix (CP) used in an OFDM symbol will make the system less sensitive to channel delay spread. Third, OFDM spreads the channel fade over multiple symbols thus making the system robust against frequency selective fading and Doppler shift. Fourth, cooperative diversity system using relays provides spatial diversity without using multiple antennas at the user end and results in power savings. Fifth, STBC requires a simple maximum likelihood (ML) decoder due to its orthogonal structure. Sixth, MIMO can increase the system capacity manifold by exploiting spatial diversity.

The preceding paragraph tends to imply that CD-OFDM or its variants have the potential to meet all desired requirements in a wireless channel. Nevertheless, It is an over simplification. Until this point in discussion, it is assumed that CD-OFDM system is perfectly synchronized and all of the preceding performance claims are based on this assumption. In order to harness all claimed benefits of a CD-OFDM system in a real world scenario, all communicating nodes must be synchronized. However, synchronization does not come cheap and is one of the most challenging tasks in any communication system.

In this dissertation, the synchronization issues related to CD-OFDM system will be elaborated and solutions will be proposed. This research work focuses on the timing and carrier frequency offset aspect of synchronization. In OFDM based systems, timing and carrier frequency offset results in ISI and ICI respectively. It is pertinent to mention that timing synchronization mechanism of an OFDM system is entirely different from single carrier systems. Similarly, OFDM is more sensitive to CFO than any other single carrier system and the problem worsens for high data rate designs because of reduction in carrier spacing. When additional relays are incorporated in CD-OFDM system, the synchronization problem becomes more complicated because all participating nodes need to be synchronized. Even further, the presence of multiple relays transforms the synchronization problem similar to that of OFDMA uplink. It is a multiple parameter estimation problem and is highly complex. Furthermore, in case of STBC, the system becomes quite sensitive to timing errors and accuracy of timing synchronizer becomes crucial.

1.3 CONVENTIONS

In addition to thesis start, relevant notations are also listed in each chapter for a handy reference. Similarly, for algorithm development, each chapter uses a slightly different architecture of CD-OFDM system and the same is described in each chapter for better understanding.

1.4 THESIS ORGANIZATION

Thesis structure is summarized below to serve as a handy reference.

Chapter 2 provides background information regarding technologies and concepts used in this thesis. A general description of OFDM is provided with special emphasis on its merits and demerits. An effort is made to explain the main reasons for selecting OFDM as the main technology for analysis in this thesis. The benefits of integrating other technologies like MIMO, Cooperative diversity (CD), OFDMA and STBC with OFDM are explored in detail. This chapter lays the foundation of CD-OFDM system that is used throughout the thesis for evaluating algorithms.

In Chapter 3, Synchronization is identified as the most crucial task to harness the boons of CD-OFDM system. It is explained that a poorly synchronized CD-OFDM system erodes all expected benefits. A mathematical model for wireless channel highlighting channel dispersion and time dispersion is presented. Channel concepts like slow fading, fast fading and frequency selectivity are explored. Models for OFDM system and for synchronization errors are discussed and are used for synchronization algorithm development and evaluation purpose in rest of the thesis.

Chapter 4 formulates the symbol-timing problem in context of CD-OFDM system and proposes a preamble and coarse timing algorithm. Literature review regarding OFDM symbol timing algorithms and subsequently a model for analyzing timing errors is presented [16].

In Chapter 5, the detrimental effects of CFO are analyzed on system performance and an overview of published CFO estimators for OFDM and OFDM based cooperative diversity systems is presented. A cooperative diversity protocol is proposed. CFO estimator and compensation mechanism is developed and evaluated. The proposed algorithms are also applicable to OFDMA uplink scenario [17].

Chapter 6 describes a fine timing synchronizer based on channel estimation. The performance of algorithm is evaluated in rigorous wireless channel [18].

Chapter 7 summarizes major contributions of this research endeavor and identifies venues for future research.

1.5 Publications and Research Papers

- M. I. Cheema and S. A. Khan, "A Low Complexity Fine Timing Offset and Channel Estimation Algorithm for Cooperative Diversity OFDM System“, International Conference on Communications and Information Technology (ICCIT-2011), Aqaba, March 2011 [18].
- M. I. Cheema and S. A. Khan, "A Robust Coarse Timing Synchronizer Design for Cooperative Diversity OFDM System”, International Conference on Communication and Electronics Information (ICCEI), Haikou, China, 22 February, 2011 [16].
- A Simple Carrier Frequency Offset Synchronization strategy for Multiple Relay Cooperative Diversity OFDM System”, Pakistan Journal of Engineering and Applied Sciences (PJEAS), Dec 2013, accepted for publication [17].

- M. I. Cheema and S. A. Khan, "A Robust Coarse Timing Synchronizer Design for Cooperative Diversity OFDM System”, International Journal of Information and Electronics Engineering (IJIEE), IACSIT Journal, Accepted and be published in Vol.3, No.6, November 2013 [16].

CHAPTER 2

COOPERATIVE DIVERSITY OFDM SYSTEM

2.1 INTRODUCTION

Last decade saw birth and subsequent maturity of few technologies and concepts that include OFDM (A), MIMO, STBC and cooperative diversity (CD). These technologies or their combination has invariably crept in most of the emerging standards as shown in Table 1. In following sections, these technologies are explored one by one to identify their desirable features. These desired features are integrated to form a CD-OFDM system that has the potential to meet most of the future-communication-system requirements. In the following chapters, different system architectures of CD-OFDM are considered and synchronization algorithms for the same are presented. Over here, the starting point is OFDM system that is a well-established technology and above all favours seamless integration with other technologies.

2.2 OFDM COMMUNICATION SYSTEM

The concept of parallel transmission over dispersive channel emerged in 1957. In its early years, OFDM was primarily used in military applications because it required bank of sinusoidal subcarrier modulators and demodulators that was not commercially viable. After 1971, OFDM system became more practical after a major design breakthrough suggested by Weinstein and Ebert that used DFT based modulator and demodulator [19] .

OFDM is mainly preferred over single carrier systems due to its robustness against frequency selective fading. Single carrier systems face severe inter symbol interference (ISI) whenever maximum delay spread τ_{max} of a channel exceeds the symbol duration T. Two solutions are prevalent to mitigate ISI in such a channel. First, ISI mitigation is done by equalization that is at times prohibitively complex. Other solution is to increase the symbol duration to make it larger than the duration of CIR. OFDM system is designed on this simple principle.

An OFDM system divides the available bandwidth (BW) into a number of parallel narrowband subchannels. The sequential input data stream is converted into a parallel low-data-rate symbol stream that modulates different subcarriers of an OFDM system. The subcarriers are made orthogonal by making the carrier spacing equal to the reciprocal of the useful symbol period and thus the name orthogonal frequency division multiplexing was coined. These subcarriers face flat fading thus easing the equalization task. OFDM is spectrally efficient because subcarriers spectrally overlap and are not band limited as is done in conventional frequency division multiplexing (FDM) systems.

The parallel transmission of data is superior to serial systems in a number of ways. First, it spreads the frequency selective (FS) fade over many symbols thus allowing reconstruction of most of these symbols even without forward-error-correction (FEC). Second, OFDM uses efficient Fourier Transform (FT) for data modulation and demodulation. Third, it generates sine functions at all subcarrier frequencies and does not require band limiting. Fourth, FDM is achieved by baseband processing instead of bandpass filtering thus complexity is reduced manifold.

Table 1: Wireless Standards based on OFDM (A), MIMO, STBC and Relays.

STANDARD / YEAR	APPLICATION	TECHNOLOGY USED	SPECIFICATIONS
IEEE 802.11a /1999	WLAN/ Wi-Fi	OFDM , WATM	54Mbps, 6GHz
IEEE 802.11b /1999	WLAN/ Wi-Fi	OFDM	11Mbps, 2.4GHz
IEEE 802.11g /2003	WLAN/ Wi-Fi	OFDM, WATM	20~54Mbps, 2.4GHz
IEEE 802.11n /2003	WLAN/ Wi-Fi	OFDM, MIMO	100~200Mbps, CP 0.8µsec
IEEE 802.16a /2003	WMAN/ WiMAX	OFDM , OFDMA, MIMO	NLOS coverage
IEEE 802.16e /2009 draft	WMAN/ WiMAX	OFDM , OFDMA, MIMO , HARQ , STBC ,SM	Adaptive modulation and FFT size, NLOS coverage
IEEE 802.16j /2009 draft	WMAN/ WiMAX	OFDM , OFDMA, MIMO , multi-hop Relays	Improved coverage, NLOS coverage
DAB/ 2007	Broadcast	OFDM	BW 1.8MHz, CP 246µsec , No Equalizer
DVB/ 2009	Broadcast	OFDM	BW 8MHz , CP 224µsec (8K)

2.2.1 Basic OFDM Design Parameters

An OFDM system has some basic design parameters that can be manipulated to meet a variety of transmission requirements in a specific channel. These parameters include useful symbol duration T_u , number of subcarriers N and modulation scheme. The duration of T_u is inversely related to subcarrier spacing f_Δ. A system with small subcarrier spacing is more sensitive to carrier frequency offsets whereas larger symbol duration makes a system robust against time dispersive channel effects.

Consider a scenario, when constellation size is not changed that is modulation is fixed. The number of subcarriers N must be increased to support a specific data throughput if larger T_u is selected. Note that number of subcarriers is directly related to FFT size and thus to the receiver complexity. In case of a mobile channel with substantial Doppler shift, a larger f_Δ is required to ensure subcarrier orthogonality. If T_u is made larger than channel coherence time then channel will become fast fading. The number of sub carriers N depends on T_u , data rate R and BW. High data rate applications require OFDM systems with thousands of subcarriers. Spectral efficiency, power budget and channel condition are the controlling factors in selection of a specific modulation scheme. OFDM allows different modulation schemes to be used for different subcarriers. A case study explaining OFDM design procedure is presented at Appendix A.

2.2.2 Merits of OFDM System

OFDM is capable of efficient transmission in a multipath channel at a comparatively lower implementation cost as compared to single carrier systems that use complex equalizers. If channel is slow-fading then OFDM allows capacity enhancement by adapting symbol constellation per subcarrier (SC) to achieve a desired SNR. OFDM can also be efficiently used for single frequency networks (SFN) used for broadcast services.

A guard interval or cyclic prefix (CP) is inserted between two OFDM blocks to avoid ISI. The use of CP results in loss of SNR and capacity but is a well-accepted tradeoff. CP is simply the replica of few leading subcarrier samples in time domain added on the trailing edge of OFDM symbol. As long as the duration of CP is larger than τ_{max} then no ISI occurs. CP converts the linear convolution of channel and signal to circular convolution thus easing the design requirements for timing synchronization .

OFDM system is highly adaptable and scalable vis-à-vis transmission channel and available resources. OFDM design allows independent selection of modulation, FFT size, CP size, subcarrier-spacing and subcarrier power to optimize the resource utility. Now a day, Cognitive radio is considered a viable solution to solve the spectrum-crowding problem and scalability of OFDM makes it a strong candidate for adoption in such systems.

MIMO is a proven technology for achieving higher throughput and its combination with OFDM technology results in simple implementations because OFDM only needs single tap equalizer.

2.2.3 Challenges of OFDM System

The OFDM systems have some inherent demerits that include stringent criterion for frequency offset synchronization, large PAPR and absence of diversity gain.

First, OFDM is sensitive to frequency offset because it disturbs the subcarrier orthogonality that is the pillar of OFDM principle. The main sources of CFO are local oscillator (LO) impairments and Doppler shift. Due to design improvements, LO impairments have been reduced to minimal but doppler shift arising from mobility cannot be avoided. In time domain, the relative movement of transmitter and receiver results in time variance of channel that gives rise to fast fading. In FD, mobility results in Doppler spread that describes the spreading of transmitted signal proportional to relative velocity and signal BW.

Irrespective of the source of CFO, it results in ICI that degrades SNR. The SNR loss in this case is proportional to the normalized frequency offset.

The second drawback of OFDM systems is the large PAPR. OFDM has large number of subcarriers and their superposition results in large fluctuations in Rayleigh distributed power profile that in turn gives rise to higher PAPR. The increase in PAPR is proportional to the number of subcarriers used in the system. Higher PAPR requires costly power amplifiers (PA) with larger linear operational range. Beyond the linear region, lies the saturation region and operating in this region results in signal distortion. PAPR mitigation is typically done using techniques like clipping and pre-coding. Clipping limits the amplitude of the input signal to lie within the linear region of amplifier. Pre-coding techniques rearrange or modify the transmitted symbols in a way to reduce the PAPR. PAPR taming is a major concern to be reckoned in OFDM design. PAPR for n^{th} OFDM symbol with signal sample $s(n,k)$ of k^{th} subcarrier is defined as:

$$(PAPR)_n = \max_{0\le k\le N-1}\left[\frac{|s(n,k)|}{E\{|s(n,k)|^2\}}\right] \tag{1}$$

Thirdly, OFDM systems are generally devoid of diversity gain because OFDM system usually mitigates the effect of multipath by increasing the symbol duration but doing so it is deprived of diversity gain. However, single antenna OFDM systems can obtain frequency diversity by employing coding and interleaving between subcarriers. In case of multipath channel, if multipath diversity is properly exploited by using maximal-ratio-combining or RAKE receiver then performance gain in terms of reduced BER is achievable.

2.3 MULTIPLE INPUT MULTIPLE OUTPUT OFDM SYSTEM

MIMOs are a vital component of the next generation communication systems that are capable of supporting high data rate. A MIMO based system uses multiple transmit and receive antennas for transmission of parallel data streams. The transmission follows different paths thus resulting in transmit and receive diversity. It significantly increases the system capacity and spectral efficiency. The capacity increases linearly with number of transmit or receive antenna whichever is minimum. The capacity is increased by using the same bandwidth but total power proportional to the number of transmit-antennas. It is a remarkable feat of performance because Shanon-Hartley law postulated a logarithmic increase in power requirement for achieving capacity gain.

In design of a wireless communication system, it is very challenging to simultaneously increase data transfer rate, increase range of transmission and reduce BER. However, OFDM based MIMO systems are known to show remarkable performance by simultaneously improving on these benchmarks. A MIMO system may provide capacity gain, diversity gain and array gain. MIMO systems may be categorized in three groups based on the implementation.

First group includes Space Time Block Codes (STBC), Delay Diversity and Space Time Trellis Codes (STTC). These are designed to use spatial diversity for enhancing power efficiency. Diversity increases link reliability by mitigating the channel fading and co-channel interference. Diversity gain is achieved due to signal transmission over several independently fading dimensions in space, time and frequency. Subsequently signals from multiple sources are combined at destination using appropriate combining techniques like maximal ratio combining or RAKE receiver. Spatial diversity is preferred at times because no extra bandwidth or time is required. Spatial diversity can be achieved by space-time coding using multiple transmit antennas. The underlying idea of STC is to add redundancy in space and time dimension to achieve spatial diversity gain without requiring CSI at transmitters.

Second group comprises of V-BLAST and similar system designs that use layered approach to increase the capacity. It exploits channel state information (CSI) for maximizing the throughput. Such systems especially BLAST uses the spatial multiplexing to send many independent data streams over different antennas. The spatial multiplexing results in capacity gain without requiring additional power. This capacity gain is only available in a rich scattering channel. Receiver uses differences in spatial signature to separate different users transmitting independent data streams. However, number of receive antennas must be equal to or greater than the transmit antenna for getting a unique solution for inverse of channel matrix.

The third group of MIMO systems provides array gain that results in improved SNR but requires channel knowledge (CIR) for coherent combining of signals.

2.3.1 Challenges of MIMO

MIMO has so many attractive features but there is a price tag for these goodies. On the down side, detection process of MIMO signal is complicated due to interference from multiple inputs in addition to ISI and noise. Implementation complexity of a high throughput MIMO system increases exponentially when ML detection is used. Similarly, channel estimation problem in MIMO requires the estimate of large number of channel links that equals the product of transmit and receive-antennas. The training pilots required for channel estimation in this case are also too large.

2.4 COOPERATIVE DIVERSITY OFDM SYSTEM

Multihop relaying has conventionally been used in satellite relays and microwave links. Now multihop relaying is seriously researched for incorporation in wireless communication systems. In wireless communications, the participating relays are primarily used to achieve diversity gain during transmission of a signal from source to destination and this conceived system is widely known as Cooperative Diversity (CD) system.

The foundation of CD concept lies on two features of wireless communications. First, wireless medium is broadcasting in nature. Second, relaying nodes practically form a distributed multiple antenna system. These two features combine the benefits of conventional relaying and multiple antenna systems in a CD system. However, the price of these advantages is requirement for additional resources like bandwidth and power for fixed data rate.

In CD system, single-antenna source can use antennas of other cooperating relays to form a distributed antenna array to transmit its data to destination. Cooperative diversity is a nascent spatial diversity method that provides the benefits of spatial diversity to single antenna systems.

A CD system may comprise of a source, multiple relay nodes and a destination node. The basic idea of a CD system is to transmit a signal from source to destination with active cooperation of relay nodes. Such system may benefit from spatial, temporal and spectral diversity depending on the design of CD system.

CD systems use three kinds of relaying strategies namely Amplify-and-Forward (AF), Decode-and-Forward (DnF) and Compress-and-Forward (CF). In AF protocol, relays only amplify the received signal and forward it to the destination without decoding. It is the simplest method for cooperation. The source node broadcasts the signal that is received by cooperation node (CN) and destination node (DN). The CN amplifies the received signal including noise and forwards it to DN. DN combines the signals received from SN and CN. As two received signals have travelled through independent fading channels so performance is improved due to transmit diversity. AF is suitable for CNs that have limited transmission power, processing capacity and foremost, system is time delay sensitive. AF mode requires CSI of all channels and this information is used to control the power of different nodes. The relays using DnF protocol decode all incoming signals arriving from source prior forwarding the same to the destination node. DnF has an edge on AF that it prunes the noise at CN by decoding the signal prior to forwarding. The relays using CF protocols compress the received signal before forwarding it to the destination.

2.5 SPACE TIME BLOCK CODED SYSTEM

STBC is used to maximize the diversity gain by combined-encoding of same data over different antennas. Alamouti code is a well-known case of STBC that uses two transmit antennas and achieves full diversity gain. It has low decoding complexity due to its orthogonal design.

The concept of Alamouti coding is simple. The two consecutive symbols s_1 and s_2 that has to be transmitted are mapped on a matrix $G_2 = \begin{pmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{pmatrix}$. Now the symbols in first and second column are simultaneously transmitted by two different transmit antenna in two symbol periods consecutively. It is pertinent to mention that entries of G_2 are linear combination of s_1, s_2 and their conjugates. This orthogonality makes the decoding process simple. The two consecutive transmitted symbols y_1 and y_2 at the single receive antenna are:

$$y_1 = h_1 s_1 + h_2 s_2 + n_1 \tag{2}$$

$$y_2 = -h_1 s_2^* + h_2 s_1^* + n_2 \tag{3}$$

where h_1 and h_2 are channel impulse response for two transmit antenna paths. The channel is assumed to remain constant for two symbol durations. The estimated received symbols $\hat{s}_1$ and $\hat{s}_2$ are:

$$\hat{s}_1 = h_1^* y_1 + h_2 y_2^* \tag{4}$$

$$\hat{s}_1 = h_1^* h_1 s_1 + h_1^* h_2 s_2 + h_1^* n_1 - h_2 h_1^* s_2 + h_2 h_2^* s_1 + h_2 n_2^* \tag{5}$$

$$\hat{s}_1 = (|h_1|^2 + |h_2|^2) s_1 + h_1^* n_1 + h_2 n_2^* \tag{6}$$

similarly

$$\hat{s}_2 = h_2^* y_1 - h_1 y_2^* \tag{7}$$
$$\hat{s}_2 = h_2^* h_1 s_1 + h_2^* h_2 s_2 + h_2^* n_1 + h_1 h_1^* s_2 - h_1 h_2^* s_1 - h_1 n_2^* \tag{8}$$
$$\hat{s}_2 = (|h_1|^2 + |h_2|^2) s_2 + h_2^* n_1 + h_1 n_2^* \tag{9}$$

The inherent orthogonality of G_2 matrix cancels out the unwanted signal components. Thereon, estimated symbols $\hat{s}_1$ and $\hat{s}_2$ are processed in ML detector.

STBC can be used in MIMO and cooperative diversity systems alike. In case of cooperative system, harnessing diversity using STBC is more challenging because all participating nodes are not fully synchronized. Moreover, time selectivity degrades the performance of STBC because its design is based on assumption of quasi-static fading channel or slow fading channel. STBC suits for a slow moving terminal when channel variations are slow in time domain. In order to address these constraints, use of OFDM for STBC coded cooperative system seems expedient because different channel paths from participating nodes are treated as multipath. Moreover, Space-time coded OFDM system is also robust against timing asynchronism because timing shift in the signal translates into phase offset in case there is sufficient CP added.

2.6 OFDM/OFDMA SYSTEM

OFDMA is multiple access technique used to support more than one user per OFDM symbol. In OFDMA, each user is allotted only a portion of the available subcarriers. OFDMA may provide multiuser diversity by intelligent subcarrier allocation because a subchannel facing severe fading may turn out to be a high gain channel for another user at some different spatial position. An OFDMA system allots several mutually exclusive bands of OFDM subcarriers to different users for simultaneous use. Underlying structure of OFDM system mitigates multiple access interference (MAI) due to inherent orthogonality among all subcarriers.

OFDMA inherits all merits and demerits of OFDM system. OFDMA can also benefit from simple frequency domain equalization to compensate channel distortions. OFDMA also favours simple subcarrier management. However, OFDMA is very sensitive to timing and frequency offsets. Insufficient frequency offset correction destroys the orthogonality of subcarriers and results in ICI and MAI. Similarly, timing errors results in high BER due to resultant ISI.

A typical OFDMA system comprises of a base node (BN) and several user nodes (UNs). The transmission from BN to UN is termed downlink and from UN to BN is called uplink. OFDMA downlink transmission is similar to conventional OFDM where each UN synchronizes independently and retrieves subcarriers assigned to it. Whereas in OFDMA uplink, several UNs independently transmit their respective information on pre-assigned subcarriers which traverse through different channels to simultaneously (ideally) arrive at BN. BN antenna implicitly combines all these UN signals and subsequently synchronization is carried out for each user separately.

An OFDMA block transmits information simultaneously from many UNs while an OFDM block only carries information from a single user. Consider a scenario, where M UNs communicate with BN by using N available subcarriers. Assume that there are Q UNs. The available subcarrier can be equally distributed among UNs. The number of assigned subcarriers may depend on data rate requirement of a specific UN. In case of equal subcarrier distribution, each UN is assigned $V = \frac{N}{M}$ subcarriers. The subcarrier index set $\mathbb{N}_m$ ranges from $[0, N-1]$. Each user is assigned a unique set of sub carriers such that the index set for two users is unique. V subcarriers are grouped together and there are total P subcarrier groups such that $M \leq P$ thus forming P subcarrier index sets $\{\mathbb{N}_m : m = 1,2, \dots, P\}$.

Three subcarrier assignment schemes (CAS) are prevalent for OFDMA. First, Subband CAS assigns adjacent subcarriers to a user and consequently is not capable of exploiting the frequency diversity because band assigned to a user is likely to face the same fade. Second, Interleaved CAS assigns uniformed spaced subcarriers to a UN and it results in frequency diversity gain. Third, Dynamic CAS assigns subcarriers to users based on data rate requirement and SNR for each user.

2.7 An Analogy - OFDMA and CD-OFDM Synchronization

The synchronization process of OFDMA is purposely explained here in detail due to its semblance with CD-OFDM system synchronization. This analogy will also help in understanding the challenges faced in CD-OFDM synchronization. Timing and frequency synchronization in an OFDMA system is completed in three phases.

First, during downlink transmission all UNs independently carry out timing and frequency estimation using the training preamble broadcast by BN. Conventional OFDM synchronization algorithms are used for OFDMA downlink synchronization because subcarriers allotted to a specific user face same timing and frequency offset. After acquiring synchronization, each UN can detect its downlink data stream. The timing and frequency-offset estimates so acquired are also used as reference for uplink transmission.

Nevertheless, residual timing and frequency offsets persist due to different propagation delays and Doppler shifts.

The second synchronization step is uplink timing and frequency offset estimation. This is a multi-parameter estimation problem because BN receives a combined signal from all UNs having distinct carrier and timing offset. The user separation at BN depends on the subcarrier assignment scheme. After user separation, offset is seperately estimated for each UN.

Third step in OFDMA synchronization is timing and frequency offset correction for each UN. Offset compensation is quiet challenging due to inherent structure of OFDMA signal. The offset compensation of one user will introduce even more offset for other UNs. Typically offset compensation is carried out by feeding back the offset to respective UN for offset correction. Nevertheless, feedback method is not feasible in channels facing severe Doppler spread. Recently, complex signal processing algorithms are also used at BN to carry out offset compensation for all UN subcarriers.

Multiuser OFDMA time synchronization is different and difficult as compared to downlink or conventional OFDM. The main reason is that subcarriers of a single OFDM symbol are assigned to different users and timing offset estimation at BS requires a prior user separation. The problem does not end here; even after estimating timing offset, its correction cannot be accomplished at BN because correction to one user will misalign other users.

2.8 CHAPTER SUMMARY

CD-OFDM is an OFDM based communication system that may incorporate other technologies and concepts like MIMO, cooperative diversity, STBC and OFDMA to meet some specific user requirement. In this chapter, the concept of CD-OFDM is explored by describing advantages and disadvantages of different technologies used in it.

CHAPTER 3

MATHEMATICAL MODELS OF WIRELESS CHANNEL AND SYSTEM

3.1 Introduction

Mathematical modeling of a system is the first step to study the dynamics of an understudy system. It helps in algorithm development and subsequent simulations to analyze the performance of algorithm at system level. In this chapter, mathematical model for wireless channel, OFDM system and synchronization errors are described for use in following chapters

3.2 Wireless Channel

Designing of almost any communication system follows the modeling of intended wireless or wired channel. The characteristics of a wired channel are generally fixed in time and frequency domain whereas wireless channel tends to vary simultaneously in both domains. The wireless transmission between two points may take a line-of-sight path or it may follow multiple paths obstructed by natural and manmade structures.

Different channel models with varied complexity have been proposed in literature to simulate the actual channel. However irrespective of model complexity, all channel models possess a basic virtue of facilitating the analysis and simulation of under design communication system. A channel model may be as simple as “free space model” that is based on inverse square law. This model is inadequate to mimic the characteristics of a practical wireless channel. In a typical wireless channel for mobile communication systems, the LOS and multiple reflections of the transmitted signal follow different paths to reach the receiver. This results in fluctuating amplitudes, phases and angle of arrival (AOA) for the received signal as shown in figure 3.1 . This phenomenon is called “multipath fading” and is characterized by large scale and small scale fading models. Large-scale fading is related to the average signal power at some location and is explained in terms of path loss and shadowing phenomenon. Path loss relates the average power of signal to the distance between receiver and transmitter. Shadowing describes the fluctuations in signal due to prominent terrain structures like buildings and hills.

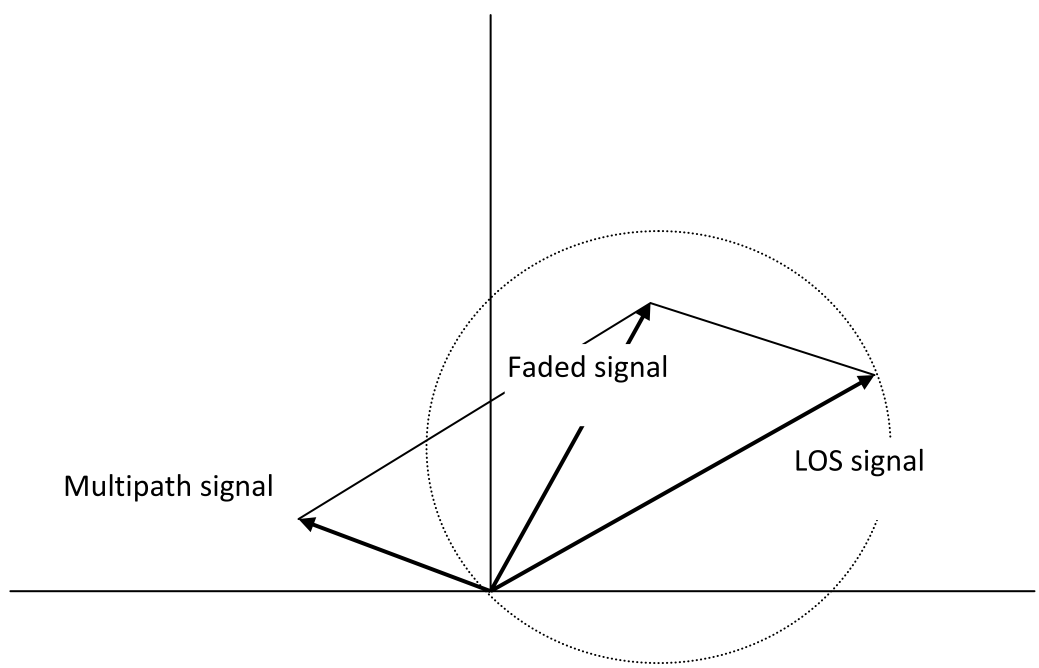

Figure 3.1: A typical outcome of destructive addition of multipath signals results in reduced magnitude.

Small-scale fading model characterizes rapid variations in signal phase and amplitude for small changes in spatial location mainly due to multipath interference. Multipath, in a wireless channel, manifests itself in three different ways namely rapid amplitude fluctuations, random frequency modulation (FM) due to varying Doppler shifts and time dispersion. In context of mobile wireless communications, small-scale fading model is the most relevant phenomenon.

3.2.1 Channel Model

In a multipath environment, the received signal is an aggregate of multiple time-delayed, phase-shifted and attenuated replicas. Channel Impulse response (CIR) is the time domain (TD) channel description that carries all necessary information to characterize a practical channel adequately. The baseband CIR of a time variant channel is:

$$h(\tau, t) = \sum_{i} |h_i(\tau, t)| e^{-j\theta_i(\tau,t)} \delta(\tau - \tau_i(t)) \tag{10}$$

where $|h_i(\tau, t)|$, $\tau_i(t)$, and $\theta_i(\tau, t)$ are amplitude , excess delay and cumulative phase shift of i^{th} multipath at time t. Note that $\theta_i(\tau, t)$ is:

$$\theta_i(\tau, t) = 2\pi f_c \tau_i(t) + \phi_i(\tau, t) \tag{11}$$

where f_c and $\phi_i(\tau, t)$ are carrier frequency and phase shift of i^{th} multipath. Delay for first arriving multipath is taken as zero i.e. $\tau_0(t) = 0$. Excess delay τ_i is the relative delay of i^{th} multipath as compared to τ_0.

If channel is assumed time invariant then CIR is:

$$h(\tau) = \sum_i |h_i| e^{-j\theta_i} \delta(\tau - \tau_i) \tag{12}$$

The Power Delay Profile $p(\tau)$ (PDP) of a multipath fading channel describes the relationship between specific multipath power versus time delay. PDP for a time invariant channel is:

$$p(\tau) = \sum_i |h_i|^2 \delta(\tau - \tau_i) \tag{13}$$

Similarly, the normalized power P_N is the cumulative of power of all multipath signals.

$$P_N = \sum_i |h_i|^2 \tag{14}$$

The K-factor is the ratio of the power of first path to other multipath. It is assumed that first arriving path is the dominant path. The value of K-factor is inversely proportional to the depth of fades. Root mean square delay spread τ_{rms}, characterizes the extent of frequency selectivity because it determines bandwidth of the fades.

The channel transfer function for a time variant channel is:

$$H(f,t) = \int_{-\infty}^{\infty} \sum_i |h_i(\tau,t)| e^{-j\theta_i(\tau,t)} \delta(\tau - \tau_i(t))\, e^{-j2\pi f\tau} d\tau \tag{15}$$

$$H(f,t) = \sum_i |h_i(t)|\, e^{-j((2\pi f \tau_i(t) + \theta_i(t))} \tag{16}$$

$H(f,t)$ varies with spatial and temporal changes and is determined by accumulating incoming multipath magnitudes and phases. $\theta_i(t)$ changes with change in location or time and results in rapid fluctuations in $|H(f,t)|$. Similarly, frequency selectivity is introduced due to varying $\tau_i(t)$ values at different frequencies.

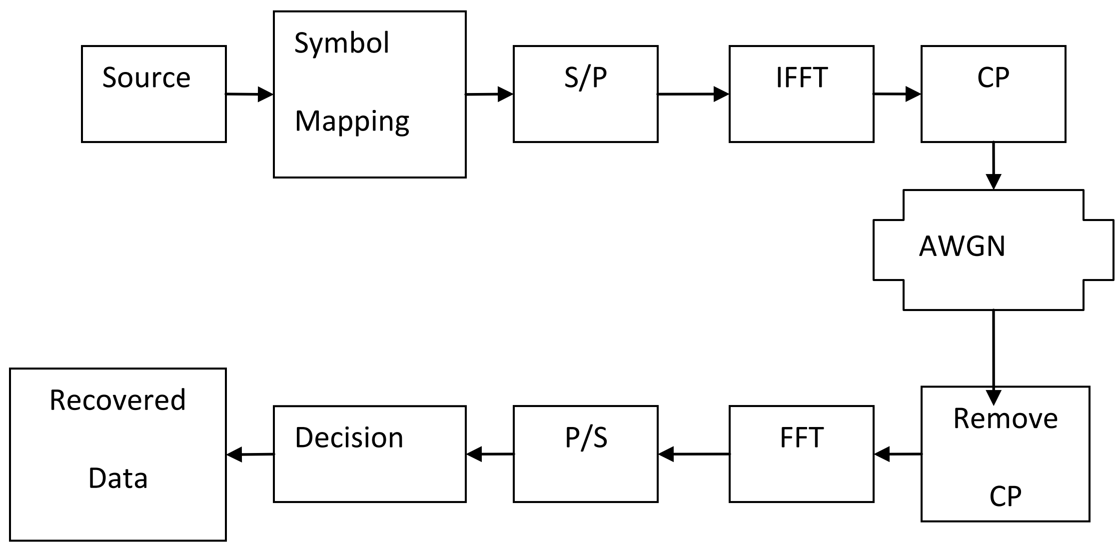

Figure 3.2: A generic baseband OFDM System

$H(f,t)$ has a complex Gaussian distribution because it is the sum of large number of random variables (RVs) with amplitude $|h_i(t)|$ and uniformly distributed phase over $[0,2\pi]$. $H(f,t)$ is zero mean in absence of a LOS component and non-zero mean otherwise. Thus $|H(f,t)|$ has a rician probability density function (pdf). In absence of LOS component, pdf of $|H(f,t)|$ reduces to Rayleigh distribution. A sampled version of CIR is used for computer simulations. The band limited CTF is:

$$H_B(f,t) = H(f,t)\, W_B(f) \tag{17}$$

where $W_B(f)$ is rectangular window to limit the signal duration in TD to $\left[-\frac{1}{T_S}, \frac{1}{T_S}\right]$. T_S is the sampling interval.

Similarly, equivalent band limited CIR is found by convolution with a $sinc$ function.

$$h_B(\tau, t) = \sum_i |h_i(t)|\, e^{-j\theta_i(t)}\, sinc(\frac{\tau - \tau_i(t)}{T_S}) \tag{18}$$

3.3 OFDM SYSTEM MODEL

An OFDM system using N point Inverse Fast Fourier Transform (IFFT) is used. Each OFDM symbol is composed of N_u $(N_u \le N)$ modulated subcarrier symbols $A_{n,k}$ where n denotes OFDM symbol time index and k denotes subcarrier frequency index. The output of IFFT is discrete time with sampling period $T_s = \frac{T_u}{N} = \frac{1}{B}$ where the bandwidth (B) of OFDM signal is $B = Nf_\Delta$. The subcarriers at both ends of the transmission band are left unused as guard bands. Subsequently, transmitted signal is band limited to less than $\frac{1}{T_s}$ bandwidth by using a transmit filter $G_T(w)$ thus making it simpler to design a T_s-spaced receiver [20]. The complex baseband transmitted signal can be described as:

$$s_n(t) = \frac{1}{\sqrt{T_u}} \sum_{n=-\infty}^{\infty} \sum_{k=\frac{-N_u}{2}}^{\frac{N_u}{2}-1} A_{n,k}\, \psi_{n,k}(t) * g_T(\tau) \tag{19}$$

Each subcarrier symbol is shaped by a rectangular pulse of length T_u and modulated on a baseband subcarrier with frequency $f_k = \frac{k}{T_u}$. A cyclic prefix (CP) of duration $T_G = G.T_s$ is added to signal to reduce ISI. Hence, complete OFDM symbol length becomes $T_c = T_u + T_G$. Note that G is the number of CP samples and T_G is the duration of CP. Now the subcarrier pulses are:

$$\psi_{n,k}(t) = e^{j2\pi\left(\frac{k}{T_u}\right)(t-T_G-nT_c)}u(t-nT_{c)} \tag{20}$$

where
$$u(t) = \begin{Bmatrix} 1 & , & 0 \leq t \leq T_c \\ 0 & , & else \end{Bmatrix} \tag{21}$$

The equivalent representation for the k_{th} sample of transmitted baseband n_{th} OFDM symbol $s(n,k)$ including CP is as:

$$s(n,k) = \frac{1}{\sqrt{N}} \sum_{m=0}^{N_u-1} A_{n,k}\, e^{j2\pi\left(\frac{k.m}{N}\right)} \tag{22}$$

where

$$-N_G \leq k \leq N-1$$

Now OFDM symbol length in a sample spaced system is $N_c = N_u + N_G$. First, assume that signal passes through an ideal channel without suffering any distortion or attenuation. Moreover, if orthogonality condition $T_u f_\Delta = 1$ is satisfied then receiver can detect the transmitted symbols $A_{n,k}$. In this case, there is no ISI and ICI.

$$A_{n,k} = \frac{1}{T_u} \int_0^{T_u} s_n(t) e^{-j2\pi k f_\Delta t} dt \tag{23}$$

Now assume a time variant CIR $h(\tau, t)$ in a multipath environment that also incorporates effect of transmit filter:

$$h(\tau,t) = \sum_i |h_i(\tau,t)|\delta(\tau - \tau_i(t)) \tag{24}$$

The channel is treated as WSS process based on the assumption of uncorrelated channel taps. The signal is received by using a flat-response receive filter in transmission frequency range.

$$r(t) = h(\tau,t) * s(t) + w(t) \tag{25}$$

$$r(t) = \sum_i |h_i(t)| s(t - \tau_i) + w(t) \tag{26}$$

The channel does not change during transmission of one OFDM symbol thus fixing delay τ_i for this duration. The received signal is sampled at rate $T_s' = T_s$ (assume) and N_c samples of n^{th} OFDM symbol are:

$$r(n,k) = \sum_i |h_i(kT_s')| s(kT_s - \tau_i) + w(kT_s) \tag{27}$$

where $-N_G \leq k \leq N - 1$

Assuming perfect synchronization, the CP samples are removed and remaining samples are demodulated using FFT operation that is equivalent to matched filtering.

$$R(n,k) = \frac{1}{N} \sum_{m=0}^{N-1} r(n,m)\, e^{-j2\pi\left(\frac{k.m}{N}\right)} \tag{28}$$

where $r(n,m) = \{r_{n,0}, r_{n,1}, r_{n,2}, \dots, r_{n,N-1}\}$ (29)

The demodulated n^{th} OFDM symbol is:

$$R(n,k) = H_{n,k}A_{n,k} + w(n,k) \tag{30}$$

and CTF is
$$H_{n,k} = \sum_i |h_i(n)| e^{-j2\pi f_k \tau_i} \tag{31}$$

3.4 Synchronization Error Model

Multicarrier systems are notoriously sensitive to synchronization errors. OFDM is not an exception and system performance substantially degrades in case symbol timing and carrier offset are not sufficiently compensated.

The transmitter sampling time T_s and receiver sampling time T_s' cannot be same because separate clocks are used. The sampling frequency offset T_Δ is measured in parts per million (ppm) and is defined as:

$$T_\Delta = \frac{T_s - T_s'}{T_s} \tag{32}$$

The transmitter and receiver use two different local oscillators and frequency difference between two oscillators is called carrier frequency offset v_Δ. Combining CFO and SFO results in a time dependent phase offset $(t) = \theta(kT_s)$. Similarly, receiver is not aware of transmitter time scale thus start of OFDM symbol is not known exactly at receiver and may have a timing offset of $\zeta_\Delta = \zeta T_s$. It is customary to embed the fractional part of TO in the CIR.

$$h_{\zeta}(\tau,t) = h(\tau,t) * \delta(\tau - \zeta_{\Delta}) \tag{33}$$

Finally, incorporating all synchronization imperfections the signal is:

$$r(t') = e^{j2\pi\theta(t')} \sum_{l} h_{\zeta,l}(t')\, s(t' - \tau_l) + w(t') \tag{34}$$

where t' is the receiver time scale. The sampled version of received signal in a multipath channel is:

$$r(n,k) = e^{j2\pi\theta(kT_s')} \sum_{l} h_{\zeta,l}(kT_s')\, s(kT_s' - \tau_l) + w(kT_s') \tag{35}$$

where

$$\theta(kT_s') = (1 + T_{\Delta})\upsilon_{\Delta} kT_s \tag{36}$$

Assuming a sample spaced system, the received signal encompassing CFO and TO effects can be alternatively described as:

$$r(n, k + \zeta_{\Delta}) = s(n, k + \zeta_{\Delta}) e^{j\left(\frac{2\pi\upsilon}{N} + \phi\right)} \tag{37}$$

where $$\upsilon = \frac{\upsilon_{\Delta}}{f_{\Delta}} \tag{38}$$

$$\phi = 2\pi n\upsilon + 2\pi \frac{nN_G}{N}\upsilon + 2\pi \frac{n(k + \zeta_{\Delta})}{N}\upsilon \tag{39}$$

υ is CFO normalized to carrier spacing f_{Δ} .

3.5 Chapter Summary

In this chapter, mathematical models for wireless channel, OFDM system and synchronization errors are presented which are subsequently used to develop, analyze and evaluate synchronization algorithms. Further, some of the channel related phenomena are also elaborated. This chapter also lists various assumptions made regarding channel and synchronization errors that make the analysis tractable.

CHAPTER 4

COARSE TIMING OFFSET SYNCHRONIZATION FOR CD-OFDM SYSTEM

4.1 INTRODUCTION

OFDM and MIMO are the technologies of choice to enable high data rate wireless communications. Commercial manifestations of these technologies include IEEE 802.11 a/n, 802.16e, 3GPP Long Term Evolution (LTE), Digital Video Broadcast for terrestrial and handheld (DVB-T/H) and DVB-T2. OFDM is capable of converting a single frequency selective channel into a frequency flat channel by dividing the available spectrum into a number of overlapping but orthogonal narrowband subchannels. Moreover, intersymbol interference (ISI) is avoided by adding cyclic prefix (CP) to each OFDM symbol. On the other hand, MIMO employs multiple antennas at the transmitter and receiver sides to open up additional parallel subchannels in spatial domain over the same frequency and time thus providing high data rates for a fixed bandwidth. The OFDM and MIMO technologies have been successfully used in a number of standards to provide high data rates in a multipath fading environment. However, in mobile communications, it is not feasible to have multiple antennas at the user end. In such scenario, cooperative diversity systems may be considered as an attractive alternative.

4.2 MOTIVATION

The combination of MIMO and OFDM is technically very promising for high data rate wireless communication systems but the requirement of more than one transmitter antenna is not feasible for portable terminal devices due to cost , size and power constraints. Cooperative Diversity techniques can be used to relieve the Source and Destination side from multiple antennas that are otherwise required to harness spatial diversity benefits to mitigate signal fading [13].

An OFDM system based on this idea may be described as Cooperative Diversity OFDM system (CD-OFDM). In CD-OFDM, distributed multiple nodes (relays) form a virtual multiple antenna array thus replacing the requirement for multiple physical antennas. Figure 4.1 shows a CD-OFDM system comprising of a Source and a Relay that provide transmit diversity similar to an open loop MIMO system (3x1). It is assumed that only one relay participates but it can be extended to any number of relays by incorporating necessary modifications.

In this chapter, a new preamble and coarse timing synchronization method is proposed for CD-OFDM system. For any OFDM based system, coarse timing estimation is required to determine the start of frame and Fast Fourier Transform (FFT) window for each OFDM symbol.

4.3 CHAPTER ORGANIZATION

This chapter is organized in various sections and the major sections are as follows. Section 4.5 presents literature review regarding timing synchronization in OFDM systems. Section 4.10 introduces the CD-OFDM system and proposed preamble structure for Decode and

Forward (DnF) mode. Synchronization (coarse timing) algorithms are developed in section 4.11. Section 4.12 presents the simulation results to validate the proposed preamble and timing algorithms.

4.4 TIMING SYNCHRONIZATION

Timing offset synchronization process is required in any OFDM receiver to acquire the start of an OFDM symbol from the complex baseband samples. The primary aim of a timing algorithm is to provide correct data samples to the FFT module. If incorrect samples are provided, it degrades FFT output and results in ISI and ICI. Timing synchronization of OFDM is conceptually different from a single carrier system. Single carrier systems use the criterion of maximum "eye opening" to find the accurate sampling time but an OFDM signal does not have anything like eye opening. An OFDM symbol comprises of hundreds of samples depending on the FFT size and timing estimate practically identifies the start of the OFDM symbol.

In OFDM, the impact of timing offset (TO) is dependent on CP length. If CP is larger than TO then result is a simple phase shift of $2\pi k f_{\Delta}\epsilon$ at k^{th} subcarrier sample. However, when TO is larger than CP then ICI results in addition to phase shift. The TO generally has a fractional part in addition to an integral part and their effect and compensation differs. The integral part is multiple of sample time and determines the placement of FFT window. The fractional part results in phase offset that is indistinguishable from the channel-induced phase offset. It is common practice to leave the fractional offset unattended at this stage and address the same as part of channel estimation problem.

Timing synchronization is conventionally carried out in three phases namely signal detection, coarse timing synchronization and fine timing synchronization. During signal detection phase, presence or absence of signal is established by comparing the received power to a threshold value. In second phase, Coarse timing synchronizer finds out the most likely start of the OFDM symbol. Correlation is generally used to establish timing with a half symbol tolerance. Coarse synchronization is not acceptable for desired receiver performance but serves to relax the design criteria for fine timing synchronizer or any other tracking algorithm that follows it. Moreover, coarse synchronization also ensures that timing point lies in the ISI free region of the CP. In final stage, fine timing synchronization further narrows the range and locks to dominant component of the signal.

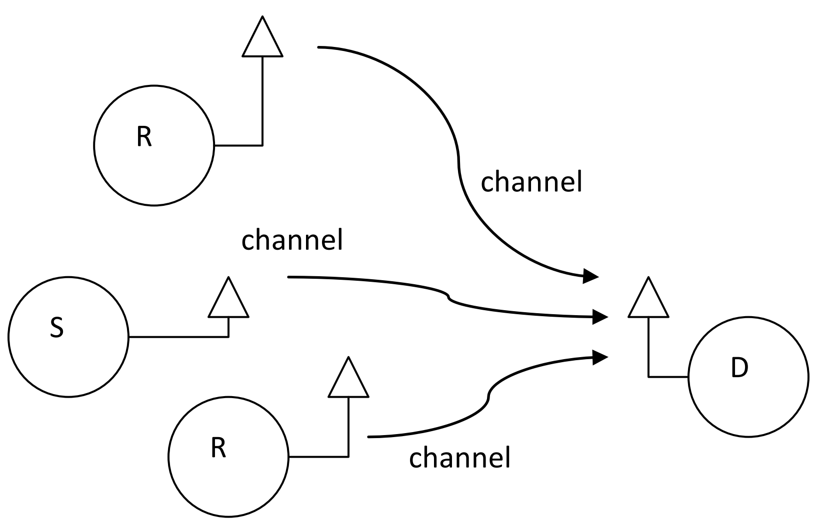

Figure 4.1: Cooperative Diversity System comprising of a Source(S), Destination (D) and multiple Relays(R) provides transmit diversity without multiple antennas at Source.

4.5 LITERATURE REVIEW

Timing algorithms can be divided into post-FFT and pre-FFT categories. Pre-FFT timing algorithms mostly exploit structure of the OFDM symbol by either using CP or a repeated training sequence.

Another classification broadly divides timing synchronization algorithms in “training based” and “correlation based” groups. The training based algorithms rely on the transmission of repeated OFDM symbols at the start of frame. These algorithms perform well and are preferred for burst transmission due to fast acquisition [21]. However, adding training is considered wasteful especially in a time variant channel because frequent training transmission is required to ensure reliable symbol alignment. Correlation based timing synchronization does not require any specialized training sequence and exploits the structure of OFDM symbol. It uses repeated pattern of CP to identify the frame start but performance is compromised in a dispersive channel.

A number of methods have been published in literature for timing synchronization in OFDM systems. The CD-OFDM systems are much more sensitive to synchronization errors as compared to simple OFDM system due to multi-user interference [22] and [12]. However, only few papers explored synchronization of OFDM based Cooperative diversity systems [23]. Most existing estimators use a preamble with repetitive structure in FD. This structure results in a robust estimator that is based on peak search of correlation among repeating preamble.

Warner proposed a three-phase symbol timing synchronizer. Phase-I detects the presence of OFDM symbol by using power detector. Phase-II uses a correlator in FD to synchronize the symbol within half sample range. Phase-III accurately identify the peak of correlator output. Finally, known training pilots are used on pre-assigned sub carriers for fine timing acquisition [24].

Nogami and Nagashima used a preamble with null symbols in their timing estimator. It detected the frame start by measuring received power. This post FFT CFO estimator uses Hanning window. It uses null symbols as preamble and is not suitable for burst communication because no way is available to distinguish between a null and intermittent burst silence. Furthermore, it performs poorly in a dispersive wireless channel [25].

Schmidl and Cox pioneered a new idea of using repetitive TD preamble and searching for peak of correlation for this preamble. It used one time domain OFDM symbol as preamble with identical halves in each frame to estimate symbol timing. The preamble can be easily formed by assigning a PN sequence at even subcarriers and keeping the odd ones empty in FD. This algorithm is robust and simple to implement. However, the timing metric has a plateau and reduces the timing accuracy [26].

Shi and Serpedin designed a novel preamble structure that sharpened the timing metric peak [27]. Their Algorithm used a repetitive training preamble with four equal length patterns like $[A \ A \ -A \ A]$. Numerous other estimators exist that concentrated on preamble structure to get an even sharper timing metric peak [28], [29].

Van de Beek based his symbol-timing algorithm on correlation of CP. However, the problem of finding frame start remains unaddressed [30].

The ML estimator timing synchronization algorithm proposed by Yang used non-coherent delay locked loop in an AWGN channel. It turns out to be a biased estimator in frequency selective channel [31].

Coulson proposed a ML estimator that used phase of subchannel pilots for timing offset estimation. However, estimator performs poorly in a frequency selective channel [32].

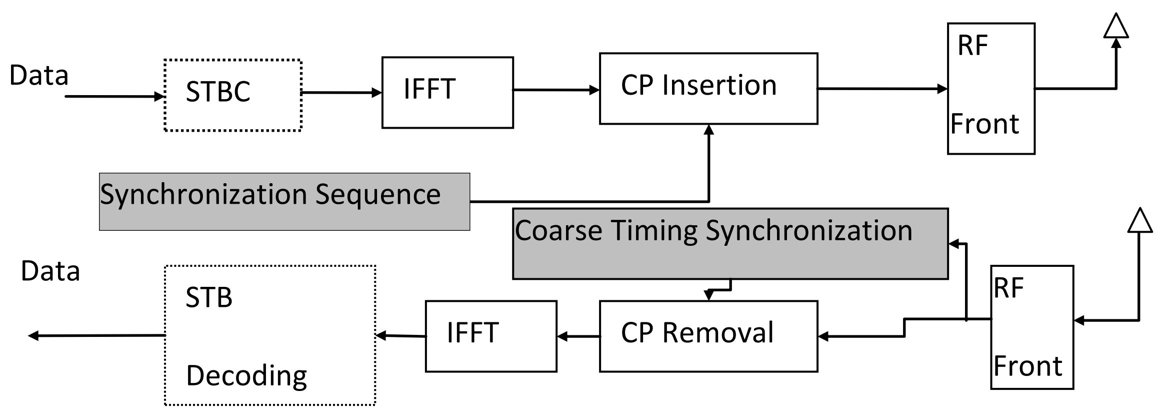

Figure 4.2: Block Diagram of Transmitter and Receiver used in a CD-OFDM System of Source, Relay and Destination nodes.

4.6 EFFECT OF OFFSET IN TIMING SYNCHRONIZATION

In order to analyze the effect of TO, ideal CFO estimation ($v_{\Delta} = 0$) is assumed. First considering a non dispersive channel with $\tau_{\max} = 0$, the received signal vector including CP is:

$$\boldsymbol{r}(n) = \{r(n, -N_G + \zeta_\Delta), r(n, -N_G + 1 + \zeta_\Delta), \dots\dots, r(n, \zeta_\Delta), \dots\dots, r(n, N-1+\zeta_\Delta) \tag{40}$$

where $\quad r(n, k+\zeta_\Delta) = r(k + \zeta_\Delta + N_G + nN_c)T_s$

Now describing the received signal in terms of transmitted signal, we have:

$$r(n, k+\zeta_\Delta) = s(n, k+\zeta_\Delta) + w(n, k+\zeta_\Delta) \tag{41}$$

After removing CP and demodulation using FFT, we get:

$$z(n,k) = \sum_{l=o}^{N-1} r(n, k+\zeta_\Delta) e^{-j\frac{2\pi lk}{N}} \tag{42}$$

$$z(n,k) = \sum_{l=o}^{N-1} \{s(n, k+\zeta_\Delta) + w(n, k+\zeta_\Delta)\} e^{-j\frac{2\pi lk}{N}} \tag{43}$$

In first case, assume that TO lies within the CP region ($-N_G \leq \zeta_\Delta \leq 0$). The received signal becomes:

$$\boldsymbol{r}(n) = \{r(n, -N_G + \zeta_\Delta), r(n, -N_G + 1 + \zeta_\Delta), \dots\dots, r(n, \zeta_\Delta), \dots\dots, r(n, N-1+\zeta_\Delta) \tag{44}$$

In this case, it is evident that only samples belonging to n^{th} OFDM symbol are used for demodulation so the result is:

$$z(n,k) = \sum_{l=o}^{N-1} \left\{ \frac{1}{N} \sum_{m=0}^{N-1} a(n,m)\, e^{j\frac{2\pi m(k+\zeta_\Delta)}{N}} + w(n, k+\zeta_\Delta) \right\} e^{-j\frac{2\pi lk}{N}} \tag{45}$$

$$z(n,k) = a(n,k)e^{j\frac{2\pi k\zeta_{\Delta}}{N}} + W(n,k+\zeta_{\Delta}) \tag{46}$$

where $$W(n,k+\zeta_{\Delta}) = \sum_{l=0}^{N-1} w(n,k+\zeta_{\Delta})\, e^{-j\frac{2\pi lk}{N}} \tag{47}$$

It is evident now that in case of a non-dispersive channel, whenever TO ζ_{Δ} falls within the range $[-N_G, 0]$ then the demodulated signal only suffers phase rotation that is constant in time. This type of phase offset does not affect the performance of coherent and differentially modulated systems that use time direction for detection.

In case-II, assume that $\zeta_{\Delta} \in \{-N_G - X, -N_G\}$ which depicts a scenario where samples of two different OFDM symbols are fed to FFT module for demodulation. The demodulated samples are:

$$\begin{aligned} z(n,k) = {} & \frac{N-\zeta_{\Delta}}{N} a(n,k)e^{j\frac{2\pi}{N}k\zeta_{\Delta}} \\ & + \frac{1}{N}\sum_{l=-N_G-\zeta_{\Delta}}^{N-1-\zeta_{\Delta}} e^{-j\frac{2\pi}{N}lk} \sum_{\substack{m=0 \\ m\neq k}}^{N-1} a(n,m)e^{j\frac{2\pi}{N}m(l+\zeta_{\Delta})} \\ & + \frac{1}{N}\sum_{l=-N_G}^{-N_G-\zeta_{\Delta}} e^{-j\frac{2\pi}{N}lk} \sum_{m=0}^{N-1} a(n-1,m)e^{j\frac{2\pi}{N}m(l+\zeta_{\Delta})} \\ & + W(n,k+\zeta_{\Delta}) \end{aligned} \tag{48}$$

The resultant demodulated signal comprises of AWGN noise (fourth term) , ICI (third term) , and ISI (second term) in addition to desired signal(first term).The desired signal has suffered attenuation and phase rotation proportional to ζ_{Δ} and subcarrier index k .Firstly, these deteriorating effects are fixed in time. Secondly, the subcarriers are no more orthogonal and system has incurred ICI. Thirdly, preceding OFDM symbol is interfering with current symbol and ISI is taking its toll.

In third case, a multipath channel is considered. The received signal is:

$$r(n,k) = \sum_{l=0}^{\tau_{max}} h_l\,(k) s(n,k-l-\zeta_\Delta) + w(n,k+\zeta_\Delta \tag{49}$$

where τ_{max} is the MCDS. The demodulated signal is:

$$z(n,k) = e^{j\frac{2\pi}{N}k\zeta_\Delta} \sum_{l=0}^{\tau_{max}} |h_l(k)|^2 \frac{(N-\zeta_\Delta)}{N} a(n,k)H(n,k) + W(n,k+\zeta_\Delta) + I(n,k+\zeta_\Delta) \tag{50}$$

where
$$\alpha(k,\zeta_\Delta) = \sum_{l=0}^{\tau_{max}} |h_l(k)|^2 \frac{(N-\zeta_\Delta)}{N} \tag{51}$$

Note that $\alpha(k,\zeta_\Delta)$ is an attenuation factor approximation and is negligible for systems using larger FFT size. A constant time phase rotation is also introduced. $I(n,k+\zeta_\Delta)$ accounts for combined effect of ISI and ICI. $I(n,k+\zeta_\Delta)$ can be modeled as zero mean RV with power $\sigma_I^2(\zeta_\Delta)$. Moreover, ISI can be avoided if timing estimate meets the condition that: $-N_G + K_{max} \le \zeta_\Delta \le 0$. In this region, only phase rotation and attenuation effect exists which can be compensated easily. One important point to note at this stage is that actual value of ζ_Δ does not give any reliable indication about the accuracy of timing estimate. In literature, most of the time, loss in SNR of the system is used to determine the accuracy of symbol timing estimator.

4.7 CONTRIBUTION

A robust coarse symbol timing offset synchronizer design for cooperative diversity OFDM system is proposed. Further, a preamble format suitable for Decode and Forward (DnF) cooperative diversity scenario is presented. One-half of the proposed preamble for Relay and Source is orthogonal and the other half is independent in time domain due to presence of null portion. This null portion also provides sufficient delay required for DnF process. The frame structure and cooperative protocol for Source and Relay is also elaborated in context of deployment of proposed timing algorithm. Furthermore, two low complexity versions for coarse timing metric estimator are also described. The performance of these algorithms is evaluated for orthogonal, independent and proposed preamble using Monte Carlo simulations. The proposed timing algorithm and preamble combination shows better probability of synch detection and timing variance even in a Rayleigh fading channel. The work in this chapter is also reported in [16] .

4.8 CRITERIA FOR PERFORMANCE EVALUATION OF TIMING SYNCHRONIZER

The primary aim of a timing synchronizer is to identify the start of frame or OFDM symbol. In doing so, the performance of a timing estimator may suffer because of two phenomenon namely “false alarm” and “missed detection”. In false alarm, estimator declares that synch or frame start is found but actually, no frame exists at that instant. In missed detection case, as name implies, the estimator fails to identify an existing frame start. The probability of missed detection and false alarm is a reliable performance measure for evaluating timing synchronizer. In this work, these metrics are mostly used for performance evaluation of timing synchronizer.

In addition, two other synchronizer states are also frequently used in literature. First, “false synchronization” means that synchronization estimate given by estimator is not accurate enough for reliable synchronization. Second, “Good synchronization” means that algorithm has locked correctly on the synchronization point.

4.9 CHAPTER SPECIFIC NOTATIONS

Small letters are used for time domain signals and capital letters are used for frequency domain signals. The node (x) represents Source(S), Relay(R) or Destination(D). The transmission phase (y) represents the Listening phase(L) or Cooperation phase(C) .The link (l) from Source to Relay, Source to Destination and Relay to Destination are denoted by SR, SD and RD respectively.

4.10 SYSTEM DESCRIPTION

A brief description of CD-OFDM system, protocol, signal and channel is presented before attacking the timing synchronization problem.

4.10.1 CD-OFDM Signal and Channel Model

A simplified block diagram for transmitter and receiver is shown in figure 4.2 that only shows system components necessary for explaining the proposed algorithms. Source, Destination and Relay are OFDM based systems. In figure 4.2, dotted blocks are used only during Cooperative Phase and shaded blocks represent proposed preamble and timing algorithm.

An OFDM system using N point Inverse Fast Fourier Transform (IFFT) is considered where each OFDM symbol is composed of N_u $(N_u \le N)$ modulated subcarrier symbols $a_{n,k}$ where n denotes OFDM symbol time index and k denotes subcarrier frequency index.

4.10.2 Frame Structure and Proposed Preamble

CD-OFDM frame comprises of two subframes: Broadcast (Listening) subframe and Cooperation subframe. Each subframe comprises of data and a time domain preamble. Figure 4.3 shows the complete frame structure and preamble.

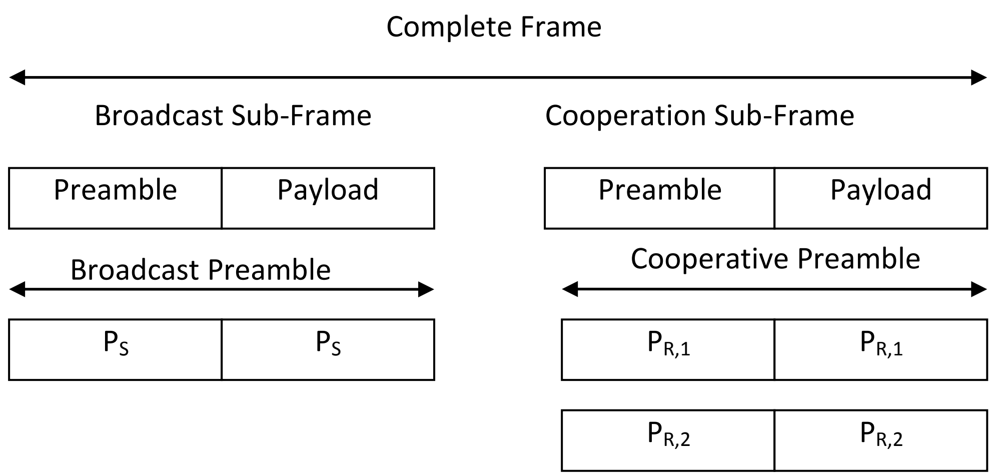

Figure 4.3: Frame Structure of CD-OFDM comprising broadcast and cooperative subframes. TD preamble for source and two relay nodes are also shown

The preamble sequence $\{p_S[n]: 0 \le n \le N_{pre}\}, \{p_R[n]: 0 \le n \le N_{pre}\}$ defines N_{pre} samples for Source (S) and Relay (R) preamble respectively with $L_{pre} \ge 1$ periods. In Cooperative Phase of CD-OFDM, the received signal is a superposition of transmitted signals from Source and Relay. P_{xy} represents the preamble transmitted by $x = S\ or\ R$ during $y = C\ or\ L$

phase.Thus, the preamble of Source and Relay need to be constituted and transmitted in such a way that mutual interference is least and accurate synchronization is possible. Orthogonal and Independent preamble formats are mostly used for multi-user systems. Figure 4.4 shows these patterns alongwith their half-length counterparts. Orthogonal preamble transmits (nearly) orthogonal patterns simultaneously from Source and Relay. Independent preamble transmits from either Source or Relay at one time thus ensuring orthogonality in time domain.

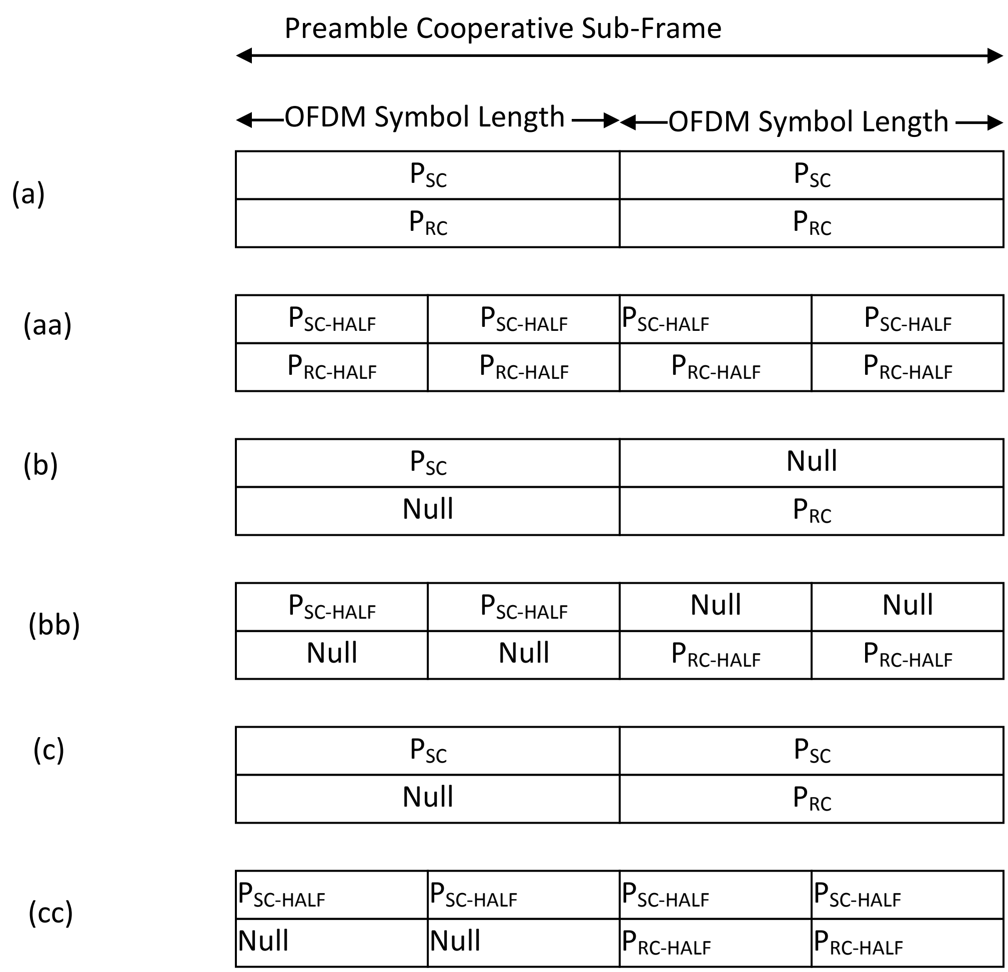

Figure 4.4: Preamble Patterns (a), (b), (c), (aa), (bb) and (cc) type.

(a) Orthogonal preamble pattern. (b) Independent preamble pattern. (c) Proposed CD-Hybrid preamble pattern for Cooperative Phase. (aa), (bb) and (cc) are the preambles with repetitive half OFDM symbol length gold sequences.

A novel preamble format is proposed that combines the best properties of orthogonal and independent preamble. It has N_{pre} equal to one OFDM symbol length and $L_{pre} = 2$. It is named CD-Hybrid (Cooperative Diversity – Hybrid) preamble because it suites best to cooperative diversity scenario. It has a null in first half of Relay preamble that permits sufficient time for decoding at Relay (DnF type) prior to retransmission. The preferred paired gold sequences of OFDM symbol length are used in this model [23], [13] and [33]. A preamble with N_{pre} equal to half OFDM symbol length and $L_{pre} = 4$ can also be used that will improve the resolution of frequency offset estimator. Two important features of preamble are:

--First, time domain preamble is used because it simplifies the time synchronization especially in burst mode transmission.

--Second, preferred pair gold sequence is used for Source(S) and Relay(R) due to its better peak-to-average-power-ratio (PAPR), autocorrelation and cross correlation properties in multiuser environment [33].

4.10.3 Space Time Cooperation Architecture

Transmission of a single frame is completed in two phases: the listening phase and cooperation phase as described in [23]. In the listening phase, only Source broadcasts to Relay and Destination without any space-time coding. During the Cooperation phase, the behavior of Relay and Destination is dictated by successful decoding at respective nodes. If Destination successfully decodes during Listening phase then it ignores all transmissions in Cooperation phase. In case of decoding failure, Destination receives the space-time coded transmission from Source and Relay for retrying decoding. Source always retransmits its space-time coded frame during Cooperation phase. Relay transmits a space-time coded frame during Cooperation phase if decoding is successful during Listening phase otherwise remains silent. The space-time coded sub frames of Source and Relay during cooperation phase are constituent half portions of the complete Listening phase space-time coded frame. There could be different ways of capitalizing from this space-time diversity setup but are out of scope of this thesis work as it focuses on timing synchronization only.

4.11 PROPOSED SYNCHRONIZATION METHOD

The purpose of coarse symbol timing synchronization is to identify the start of frame so that cyclic prefix could be removed and set of samples for subsequent FFT operation is flagged correctly. Timing synchronization during Listening phase is similar to any other OFDM system. However, in Cooperation phase, synchronization becomes a bit different due to multi-user scenario. Taking symbol timing offset and carrier frequency offset into consideration, the k received signal samples $r_{x,y}(k)$ at node $(x = R \; or \; D)$ for Listening Phase$(y = L)$ become:

$$r_{x,L}(k) = \exp(j\varphi_l) \exp\,(j\frac{2\pi k v_l}{N}) \sum_{i=0}^{K-1} h_{l,i} s_l\big(k - \tau_{l,i}\big) + w(k) \qquad (52)$$

and k received signal samples for Cooperation phase $(y = C)$ at destination (D) are:

$$r_{D,C}(k) = exp(j\varphi_{SD})\, exp\,(j\frac{2\pi k \nu_{SD}}{N}) \sum_{i=0}^{K-1} h_{SD,i} s_{SD}(k - \tau_{SD,i}) + exp(j\varphi_{RD})\, exp\,(j\frac{2\pi k \nu_{RD}}{N}) \sum_{i=0}^{K-1} h_{RD,i} s_{RD}(k - \tau_{RD,i} - \rho) + w(k) \quad (53)$$

where ν_l is the carrier frequency normalized by the subcarrier spacing , φ_l is an arbitrary carrier phase factor , $h_{l,i}$ is i_{th} channel impulse response tap , $\tau_{l,i}$ is timing offset and ρ is timing offset between received signal from Source and Relay and is assumed to be less than cyclic prefix..

4.11.1 Coarse Timing Estimation

For derivation of timing algorithm, it is assumed that target signal is preceded by channel noise. This algorithm uses difference between squared distances of two parts of M samples each separated by Q samples for calculating timing metric. Three different versions of the algorithm are presented below with decreasing order of complexity. Type-3 algorithm is specially suited for burst transmission.

Type-1

$$\gamma_{coarse}(d) = \sum_{i=0}^{M-1} \frac{(|r(d+Q+i|^2 - |r(d+i|^2)}{(|r(d+Q+i|^2 + |r(d+i|^2)} \quad (54)$$

Type-2

$$\gamma_{coarse}(d) = \frac{1}{\alpha(d)} \sum_{i=0}^{M-1} (|r(d+Q+i|^2 - |r(d+i|^2)$$

where

$$\alpha(d) = \sum_{i=0}^{M-1} |r(d+Q+i|^2 + |r(d+i|^2 \quad (55)$$

Type-3 $$\gamma_{coarse}(d) = \frac{1}{\beta}\sum_{i=0}^{M-1}(|r(d+Q+i|^2 - |r(d+i|^2) \qquad (56)$$

where β is a scaling factor that is dependent on SNR but for sake of simplicity it may be fixed. This thesis uses $M = \beta = Q = \frac{N}{2}$.

The coarse timing estimator flags the largest amplitude of the timing metric as the start of frame ($\hat{d}_0$) such that it is greater than coarse timing metric threshold γ_{th}.

$$\hat{d}_0 = arg_{d}^{max}\,\{\gamma_{coarse}(d)|\,\gamma_{coarse}(d) \geq \gamma_{th}\,\} \qquad (57)$$
$$d = 0,1,\ldots\ldots,\frac{N}{2}$$

Estimated start of frame ($\hat{d}_0$) is pre-advanced by d_{adv} samples to make the estimator robust in case of multipath channel so that it remains in the ISI free region.

$$\hat{d}_{coarse} = \hat{d}_0 - d_{adv} \qquad (58)$$

4.12 PERFORMANCE EVALUATION, SIMULATION RESULTS AND DISCUSSION

The performance of proposed algorithms is evaluated through computer simulations. The CD-Hybrid preamble with N_{pre} equal to one OFDM symbol length and $L_{pre} = 2$ is used. The proposed preamble exhibits good PAPR, autocorrelation and cross correlation properties that can also be capitalized in development of frequency offset and channel estimation algorithm [33].

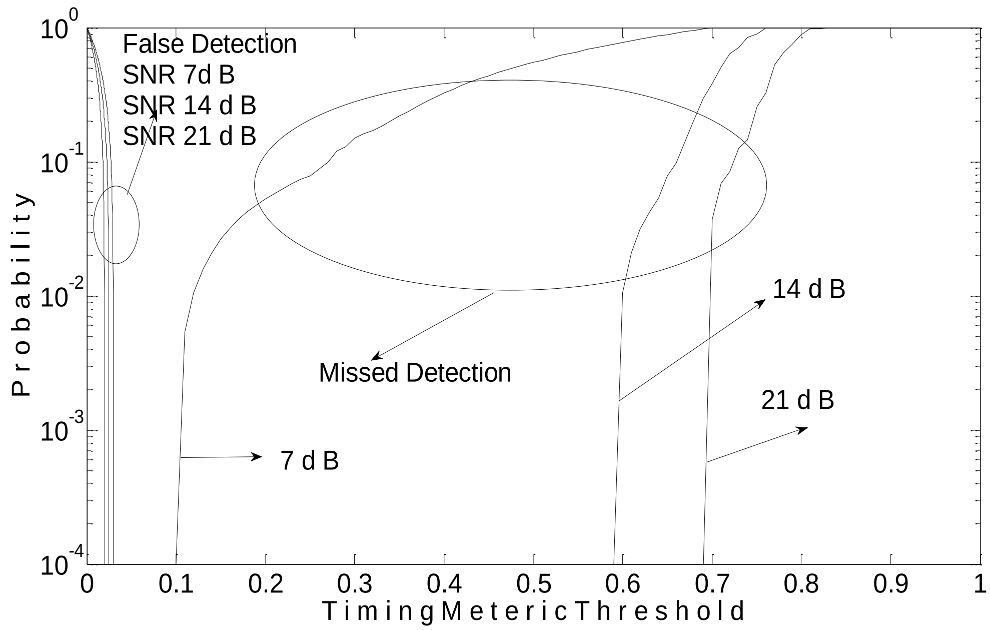

Figure 4.5: Synchronization detection performance of Coarse Timing Synchronizer (Type-3) during Listening phase.

The Cooperative Diversity network comprises of one Source node, one Relay node and one Destination node. Geometric gain G_l of 0dB is used for all considered cases for fair comparison. All nodes are OFDM based systems using QPSK modulation. All simulations are run in baseband and no pulse shaping or frequency up-conversion is done. The Rayleigh, Rician and static ISI channels are used that have 16 taps with four taps spacing. Rayleigh fading channel has exponential power delay profile with first-to-last tap ratio of 20 dB. K-factor for Rician channel is four.

In Figure 4.5, Coarse timing method (type-3) is used for different SNR scenario during Listening phase. This figure shows results for SD link using 1024 subcarrier OFDM system with 10% guard interval. Transmitted Frame includes “time domain preamble” and “information samples” of two OFDM symbol lengths each. Frame is prefixed and suffixed by “noise only samples”. In order to evaluate the probability of missed detection(P_{missed}) and probability of false detection(P_{false}),10^5 simulation runs are performed for a Rayleigh channel. Simulation shows that P_{missed} and P_{false} curves are distinctively separated which results in good synch detection probability.

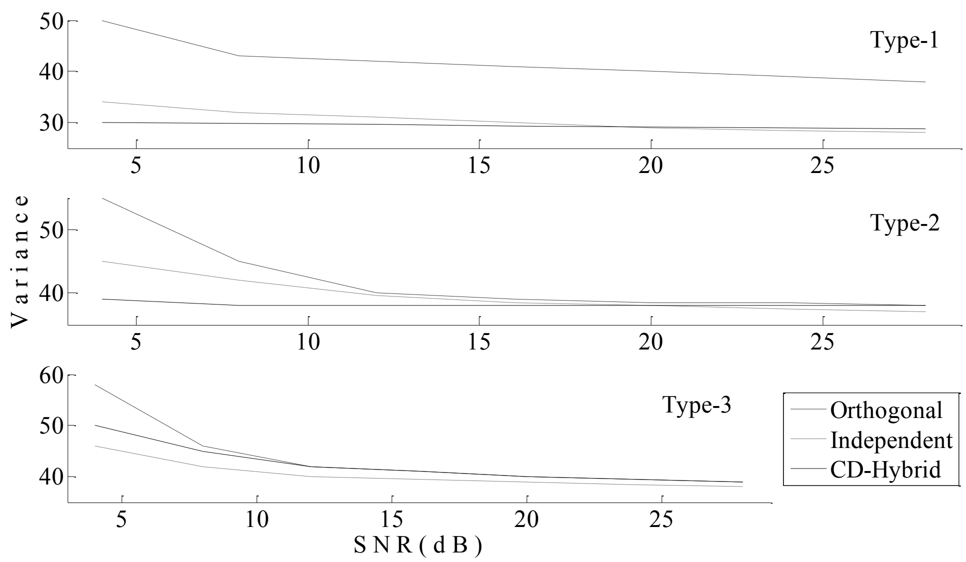

Figure 4.6: Variance (sample)^2 of Coarse Timing Metric (Type-1, Type-2, Type-3) for Cooperation Phase.

In Figure 4.6, variance of timing metric for Type-1, Type-2 and Type-3 algorithm for cooperative phase in Rayleigh channel is compared for orthogonal, independent and CD-Hybrid preamble using 10^4 simulation runs. For Type-1 algorithm, CD-Hybrid preamble performs better for low SNR but Independent preamble leads marginally on high SNR. For Type-2 algorithm, all three preambles perform equally well on high SNR but are overall inferior to Type-1. For Type-3 algorithm, Independent preamble performs better than CD-hybrid. It can be safely inferred that CD-Hybrid preamble performs better than orthogonal preamble in all cases. Independent preamble performs marginally better than CD-Hybrid for Type-3 algorithm but is less robust than proposed preamble.

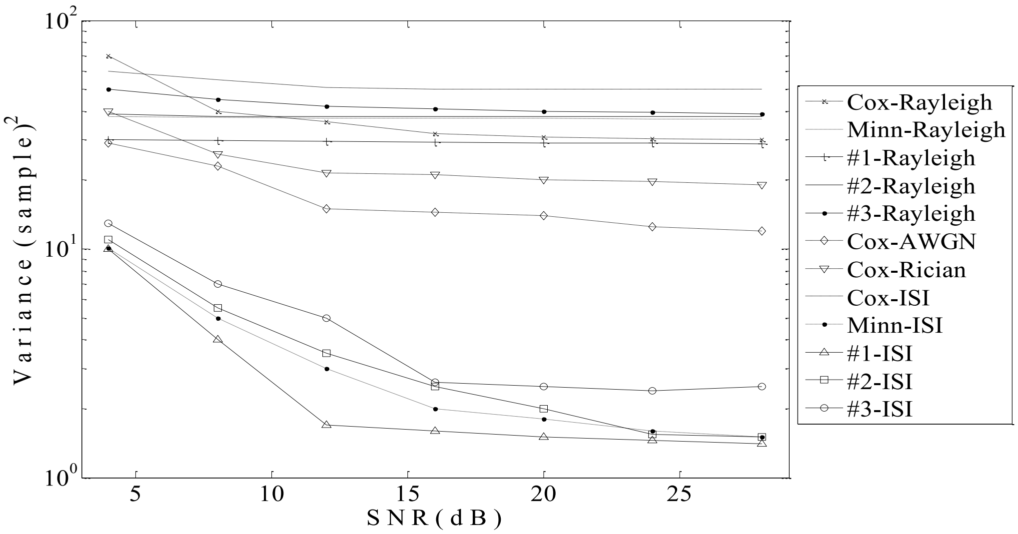

Figure 4.7: Variance of proposed Coarse Timing Metric (Type-1, Type-2, and Type-3) compared with other algorithms during cooperation phase.

In Figure 4.7, a comparison of proposed algorithms using CD-Hybrid preamble is shown with other existing algorithms like Cox [34] and Minn [28]. The AWGN, static ISI, Rician and Rayleigh channels are used for 10^4 simulation runs. For AWGN and Rician channel, proposed and Minn's algorithm give (near) zero variance so these are not shown. In case of ISI channel, Minn performs marginally better than Type-2 (#2) and Type-3 (#3) but Type-1 (#1) gives a superior performance. For Rayleigh channel, proposed Type-1 algorithm performs better than Minn and Cox. More importantly, in this case, variance remains constant for different SNR values.

4.13 Chapter Summary

CD-OFDM systems may be widely adopted in future mobile communication systems due to their favorable features. In a step towards that direction, this chapter presents and evaluates performance of a preamble that especially suites DnF based CD-OFDM system. Moreover, a coarse timing algorithm and its low complexity versions were also described and their performance is compared with already existing algorithms. Simulation results show that performance of proposed algorithms using CD-Hybrid preamble is better than reference algorithms in multi-user environment.

CHAPTER 5

CARRIER FREQUENCY OFFSET SYNCHRONIZATION FOR CD-OFDM SYSTEM

5.1 INTRODUCTION

Cooperative Diversity Orthogonal Frequency Division Modulation (CD-OFDM) systems are very sensitive to synchronization errors. In CD-OFDM, synchronization is more complex because all cooperative nodes (CNs) have their own frequency oscillator and different channel path which results in different timing and carrier frequency offset (CFO) for each node. Consequently, each node has to be synchronized separately without affecting the synchronization process of other nodes. All CNs transmit simultaneously during cooperation phase (C-phase) and their aggregate signal is received at the destination node. CD-OFDM systems pose a challenging synchronization problem but are ideal for accruing diversity in small mobile units that cannot afford multiple transmit antennas like MIMOs. Figure 5.1 shows a comparative depiction of MIMO and CD-OFDM system.

Synchronization is a tedious job and various design parameters are interlinked that makes harmonizing the tradeoffs even more complicated. Timing asynchronism problem in a multiuser environment is eased by using OFDM because it is quite robust to small timing errors due to presence of CP and longer symbol duration. The main reason is that; in OFDM, small residual timing offset (TO) results in phase shift in FD channel that is conveniently addressed by channel estimator. It is pertinent to mention that longer symbol duration in OFDM relaxes the timing synchronization problem but makes the system vulnerable to CFO. Further, inaccurate frequency synchronization results in residual frequency offset thus making the channel time variant. It results in inter carrier interference (ICI).

In CD-OFDM like OFDMA, the choice of CFO estimation and correction scheme is largely dependent on the type of carrier assignment scheme (CAS). In sub-band CAS, cooperating nodes (CNs) are allotted contiguous chunks of subcarriers. The interleaved CAS assigns equally spaced subcarriers to each cooperating node (CN). Interleaved CAS benefits from frequency diversity offered by multipath. The most widely used solution to resolve CFO problem in OFDMA is to feedback the estimated CFO back to the CNs for correction because correction of CFO at destination requires user separation. This scheme requires additional bandwidth and power. However, in case of sub-band CAS, user separation is possible by using filter bank thus conventional CFO estimation and correction methods can be used. In case of interleaved CAS, iterative interference cancellation schemes are typically used but these schemes are prohibitively complex.

5.2 CONTRIBUTION

A unique frequency domain (FD) preamble is proposed for each CN during C-phase that will allow simple separation of cooperative nodes. These FD multiplexed preambles make the synchronization problem identical to OFDMA uplink. OFDMA system typically uses highly complex iterative CFO estimators for uplink synchronization like ESPIRIT. ESPRIT exploits the shift invariance property of signals and requires Eigen decomposition of the covariance matrix. The high computational complexity renders ESPRIT less feasible in a real-time application. However, a simple single-shot CFO estimator is proposed that uses repeated preamble of two OFDM symbols duration. The proposed method is computationally efficient because it relies on FFT operation for user separation and interference mitigation. Subsequently, time domain (TD) multiplication is used for CFO correction of each CN. Furthermore, a CD-OFDM protocol for data transmission is presented that suites the proposed estimator and harnesses spatial diversity. The proposed estimator shows good statistical results during simulations in AWGN and Rayleigh environments. During evaluation, estimator variance, mean square error and symbol error rate are used as performance measure. The results in this chapter are also reported in [17].

5.3 CHAPTER ORGANIZATION

This chapter is organized as follows. Section 5.4 presents the literature review of various CFO estimation algorithms and section 5.5 describes the effects of CFO on OFDM system performance. Section 5.6 introduces the CD-OFDM system for DnF mode. CFO estimation and correction are developed in section 5.7. Section 5.8 presents the simulation results to validate the proposed algorithms.

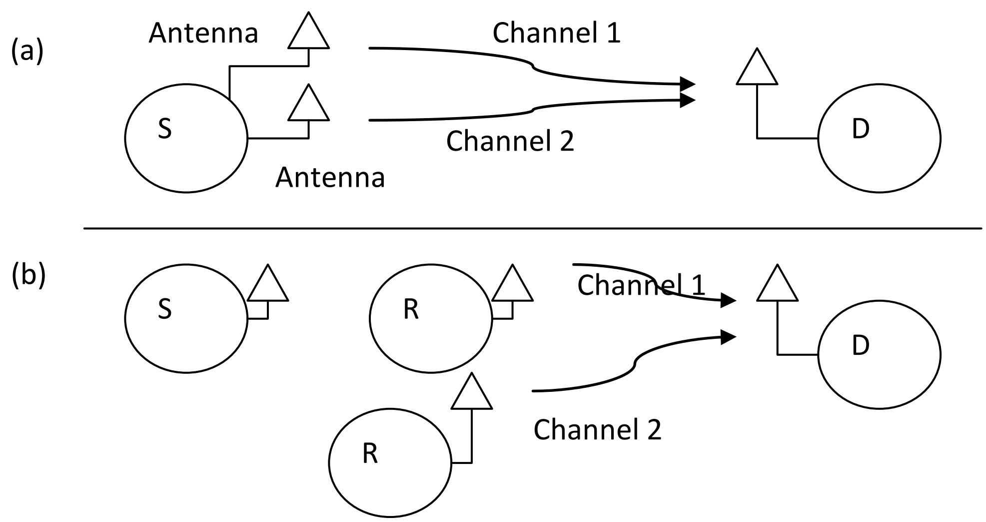

Figure 5.1: (a) MIMO (2x1) (b) Cooperative relay system can also provide transmit diversity similar to MIMO.

5.4 LITERATURE REVIEW

The carrier frequency offset estimation problem in a CD-OFDM system has many similarities with OFDMA uplink. In this section, literature review is presented in a way to highlight interconnect between published research work for OFDM, OFDMA and CD-OFDM systems. CFO problem for single user OFDM system has been extensively explored in literature and similarly many methods have been presented for OFDMA [35]. In most of the modern communication systems, timing recovery precedes carrier recovery and both estimators share same training preamble for offset estimation. However, in some cases dedicated training may also be used based on design. Timing Offset imparts a phase rotation that is dependent on the index of subcarrier in FD and at times, this property is exploited for estimation purpose.

Moose proposed a post FFT CFO estimator that was based on ML estimation. The algorithm is based on comparison of phases of two repeated received training OFDM symbols. The phase shift of subcarrier pair of repeated received symbols is due to the frequency offset because modulation phase values and channel impact are identical for both training symbols. This estimator has an acquisition range of half subcarrier spacing and timing synchronization is assumed to be already achieved. Moose further explained that shortening the period of repeated training pattern increases the acquisition range of algorithm. Nevertheless, shortening of training period deteriorates the performance of estimator. More importantly, training period needs to be larger than the CP otherwise ICI will distort the sub carrier phases used for CFO estimation [36].

Classen and Meyr proposed a two-stage CFO estimation algorithm that used variable number of uniformly spaced frequency domain pilots in atleast two OFDM symbols. The structure of this estimator is especially suitable for high order modulation systems operating in frequency selective environment. The acquisition phase has a range of multiple subcarrier spacing and offset is reduced to half carrier spacing. The acquisition is carried by FD correlation of received pilots with known pattern. The tracking phase further reduces the CFO error. This iterative algorithm is computationally demanding [37].

Sari used equally spaced FD pilots embedded into the data symbol as training. The remaining subcarriers are used for data transmission. Moreover, null sub carriers are used at both ends to OFDM symbol to help identify the shifted pilot positions [38].

Schmidl and Cox (S&C) modified the algorithm proposed by Moose and Classen. Their algorithm reduced the complexity substantially and enlarged the CFO estimation range to the multiple of subcarrier spacing. It also uses two OFDM symbols as preamble. The first OFDM symbol has two identical halves and is used for timing estimation and fractional CFO estimation. The second training symbol has a PN sequence that is differentially encoded on the odd frequencies and another PN sequence at even frequencies. The second training symbol is used for estimation of integral CFO part. The fractional CFO estimation is done by exploiting the difference in identical halves of the first received training symbol. Its working principle is that the two identical halves are affected similarly by channel and the only difference is that of CFO. This design is based on an assumption that MCDS is less than CP and prior acquisition of timing. The integral CFO estimation is done post FFT by using the PN sequence to resolve the frequency ambiguity [26].

Morelli and Mengali (M&M) extended the S&C algorithm by using L repeated parts ($L > 2$) in single OFDM training symbol. It has an acquisition range of $\pm\frac{L}{2}$ and reduced training overhead [39].

Beek proposed a CFO tracking algorithm for different users in the multiuser uplink of an OFDM-based system. This algorithm is applicable to OFDM uplink where users are separated in sub-bands of adjacent subcarriers. CFO estimation and correction is done in steps. First, CFOs for all users are estimated at the BS. The estimation at BS is done by exploiting CP redundancy and does not need additional pilots. Second, estimated CFOs are fed back to respective users for coarse LO adjustment. However, in a non-coherent system, this estimator incurs a 0.7 dB penalty as compared to ideal CFO estimation. Further, performance suffers as the number of subcarriers in a sub-band decreases and SNR for each user is different [30].

Barbarossa proposed a CFO estimation method for sub-band CAS OFDMA uplink with quasi-synchronous and asynchronous user nodes. This CFO estimator does not require known preamble and its performance is not affected by presence of channel nulls. It exploits null subcarriers inserted in subband of each user. This iterative method updates CFO estimates until the energy of the DFT outputs corresponding to null subcarriers becomes minimum. However, the claim of not using known preamble is not justifiable because use of null subcarriers is similar to the use of known preamble except that null symbols may save some power. Further, it is quite complicated because estimation requires a 2-D grid search [40].

Cao proposed a method for estimating the CFOs of all users simultaneously in OFDMA uplink using interleaved CAS. This structure-based deterministic estimation algorithm exploits the inner algebraic structure of the uplink signals for CFO estimation. Its working is based on basic fact that signal from each user has a special periodic structure in an interleaved OFDMA block. In first step, this algorithm arranges the received signals into a matrix form to reduce the number of unknown CFOs to the number of users. In second step, a high-resolution signal-processing technique like MUSIC [41] is used to estimate deterministically the CFOs of all users. More importantly, this algorithm is computationally efficient because it uses one OFDMA block for estimation and the number of unknown parameters equals the number of users instead of total number of subcarriers. It does not require any training block or pilot sequence for CFO estimation. However, efficient working of algorithm requires that CFOs of all users must be within half the subcarrier spacing and uplink signals are quasi-synchronous. Further, estimation accuracy degrades as the number of active users approaches the number of available subchannels [42].

Morelli proposed a CFO estimation method for OFDMA uplink using generalized CAS. In generalized CAS, BS exploits CSI to assign the most suitable subcarriers to each user .This dynamic resource allocation scheme is more flexible than the subband or interleaved CAS. Generalized CAS can provide multiuser diversity because subcarriers are dynamically allocated such that a deep fade subcarrier for one user is immediately assigned to some other user where it happens to be high gain subcarrier. Nevertheless, dynamic allocation policy makes the synchronization task formidable. CFO estimation uses the ad hoc reasoning to compute estimates of frequency offsets of a new user entering the network. It uses feedforward estimation and allows synchronization in only two OFDM blocks using repetition of fixed pilot symbols. Its major limitation is the assumption that CFO estimation and correction for other users have already been done [43].

The exact ML solution of multiple parameter estimation problem turns out to be too complex in OFDMA uplink using generalized CAS so alternative schemes are extensively explored by researchers. SAGE algorithms [44] are recursive approximation to the ML estimator in which previous estimates of desired parameters are exploited to weed out the MAI. Pun proposed an iterative scheme that jointly performs CFO estimation and channel estimation. In each iteration, the superimposed signals arriving at the BS are separated by using SAGE algorithm. These separated signals are subsequently processed by an Expectation conditional maximization (ECM) algorithm that updates CFO estimates and channel estimation for each user. Above all, CFO compensation is done at BS and results in overhead reduction. This feature makes it suitable for high mobility environments that require frequent updates of estimates and solves the parameter-aging problem due to feedback delays. It can estimate larger CFOs but computational requirements are too much for a practical system [45].

CFO estimation for CD-OFDM system is still open for research and is drawing attention of researchers. The estimation of CFO in cooperative environment turns out to be a multiple parameter estimation problem and its maximum likelihood (ML) solution requires a multidimensional (M-D) space search. It makes the exact ML solution extremely complex and researchers resorted to transforming M-D search problem into a series of single dimension searches [46] , [45] and [47].These iterative CFO estimation algorithms are still computationally complex and require proper initialization for convergence.

Choi proposed a reduced complexity, post FFT scheme for CFO correction in multiple-user environment that used circular convolution [48]. However, this scheme cannot be used for timing correction and suffers due to multiple access interference (MAI).

The MAI issue in Choi algorithm was addressed by incorporating an iterative interference cancellation scheme [49] but complexity was substantially increased. Some non-iterative methods were also proposed for CFO estimation and mitigation. One such CFO mitigation algorithm used long CP mitigation but required complex matrix inversion for each FFT block

[50]. Similarly, an algorithm [51] used virtual subcarriers and subspace decomposition for CFO estimation. Another method is proposed in [52] that pre-corrects respective CFOs at relays instead of destination but this algorithm is based on assumption that relay knows CFO between it's receive and transmit paths.

5.5 EFFECT OF OFFSET IN CARRIER FREQUENCY SYNCHRONIZATION

In OFDM system, subcarriers lose their mutual orthogonality due to shift of received signal in FD and the phenomenon is generally termed as Carrier Frequency Offset (CFO). In order to study the effects of CFO on system performance, ideal timing synchronization ($\zeta_{\Delta} = 0$) is assumed.

In first case, whenever normalized CFO v is an integral multiple of carrier spacing, the result is shift of modulated subcarriers by v units. In this case, subcarriers remain mutually orthogonal; however, received symbol position at DFT output is altered.

The second case, when v is not an integral multiple is more troublesome and is studied in detail.In an AWGN channel, the received signal is:

$$r(n,k) = s(n,k)e^{j\frac{2\pi v(k+nN_c)}{N}} + w(n,k) \tag{59}$$

Taking FFT of received signal for demodulation purpose, we get:

$$z(n,k) = \sum_{l=0}^{N-1} \left\{ s(n,l)e^{j\frac{2\pi v(l+nN_c)}{N}} + w(n,k) \right\} e^{-j\frac{2\pi kl}{N}} \tag{60}$$

$$z(n,k) = \frac{1}{N}\sum_{l=0}^{N-1}\sum_{m=0}^{N-1} a(n,m)e^{j\frac{2\pi lm}{N}}\, e^{j\frac{2\pi v(l+nN_c)}{N}} e^{-j\frac{2\pi kl}{N}} + W(n,k) \tag{61}$$

$$z(n,k) = a(n,k)\left(1 + e^{j\frac{2\pi v n N_c}{N}}\right) f_N(v) + e^{j\frac{2\pi v n N_c}{N}} + \sum_{l=0}^{N-1} \sum_{\substack{m=0 \\ m\neq k}}^{N-1} a(n,m) e^{j\frac{2\pi l(m-k+v)}{N}} + W(n,k) \tag{62}$$

where $$f_N(y) = \frac{sin(\pi y)}{N sin\left(\frac{\pi y}{N}\right)} e^{j\frac{\pi y(N-1)}{N}} \tag{63}$$

using $$\phi(n,k,v) = \frac{2\pi v n (N + N_{G)}}{N} \tag{64}$$

$$z(n,k) = \frac{1}{N} e^{j\phi} \left\{ a(n,k) \sum_{l=0}^{N-1} e^{j\frac{2\pi l v}{N}} + \sum_{l=0}^{N-1} \sum_{\substack{m=0 \\ m\neq k}}^{N-1} a(n,m) e^{j\frac{2\pi l(m-k+v)}{N}} \right\} + W(n,k) \tag{65}$$

$$z(n,k) = \frac{1}{N} e^{j\phi} a(n,k) f_N(v) + \frac{1}{N} e^{j\phi} \sum_{\substack{m=0 \\ m\neq k}}^{N-1} a(n,m) f_N(v+m-k) + W(n,k) \tag{66}$$

The demodulated signal comprises of noise (n,k) , the desired signal $a(n,k)$ and ICI (second term).The desired signal is attenuated and rotated.

5.6 SYSTEM DESCRIPTION

A brief description of CD-OFDM system, protocol, signal and channel is presented before attacking the CFO estimation and compensation problem.

5.6.1 Cooperative Diversity Protocol

We use two-phase cooperative system comprising: broadcast phase (B-phase) and cooperation phase (C-phase) as described in [18] [51] [23]. Figure 5.2 shows the system that comprises of a destination node (DN), a source node (SN) and M relay nodes (RNs). All RNs operate in DnF mode.

In the B-phase, only SN broadcasts preamble followed by information blocks using all OFDM subcarriers. The RNs and DN attempt to decode it and failure or success in decoding is determined by computing the frame check sum (FCS). The DN transmits acknowledgment (ACK) or no-acknowledgement (NAK) signal based on result of decoding. The ACK/NAK signal is used for RN selection in next phase and for coarse timing and frequency synchronization at SN and RNs. This arrangement ensures synchronous arrival of data at DN and synchronous detection.

During the C-phase, if an ACK is transmitted by DN then SN and RNs do not transmit. However if DN transmits a NAK then M RNs that have successfully decoded the SN transmission and received NAK from DN start transmission simultaneously. Each RN transmits its unique FD preamble and data block on CAS mapped subcarriers. Any number of RNs can participate in C-phase but this work used two RNs (i.e. $M = 2$).

During C-phase, DN receives a signal that is aggregate of all signals transmitted from RNs. Consequently, DN faces multiple-parameter estimation problem because each RN operates independently with its separate oscillator and channel path. It results in independent CFO and TO for each RN. It makes the synchronization problem in C-phase identical to that of uplink OFDMA.

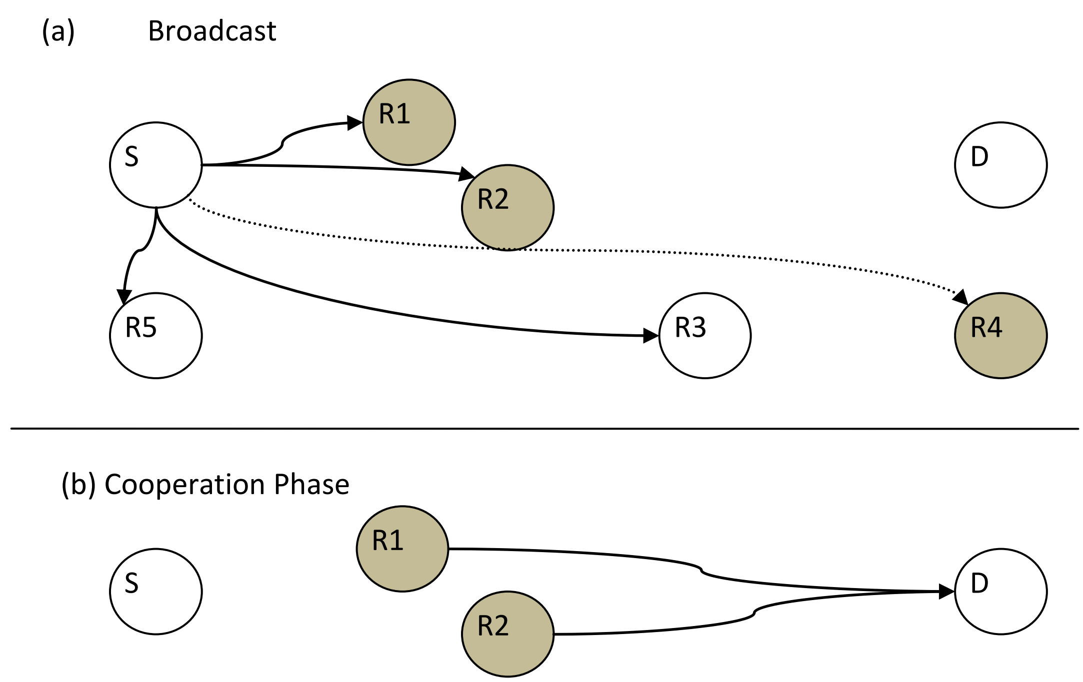

Figure 5.2: Schematic of Cooperative Diversity protocol (a) Broadcast and (b) Cooperation phase

(a)In Broadcast phase only source node transmits. Solid and dashed link lines indicate successful and failed decoding respectively at a nodes. Nodes are shaded to indicate the successful receipt of NAK signal from destination. (b) In Cooperation phase, only those nodes participate that have successfully decoded the source transmission and have also received the NAK from destination.

B-phase synchronization is similar to single user OFDM synchronization and any of the known method can be used for synchronization [33], [31], [28], [53] and [54]. In this thesis, we have only tackled the C-phase CFO synchronization problem being more challenging

5.6.2 Frame Structure and Preamble

The transmission of a single frame is completed in two phases. Transmitted frame comprises of two subframes: broadcast subframe and cooperation subframe that are transmitted using OFDM [23]. Frame structure and preamble are shown in figure 5.3. Each subframe comprises of data and a FD broadcast preamble (FDBP) or cooperation preamble (FDCP) that is used for CFO estimation.

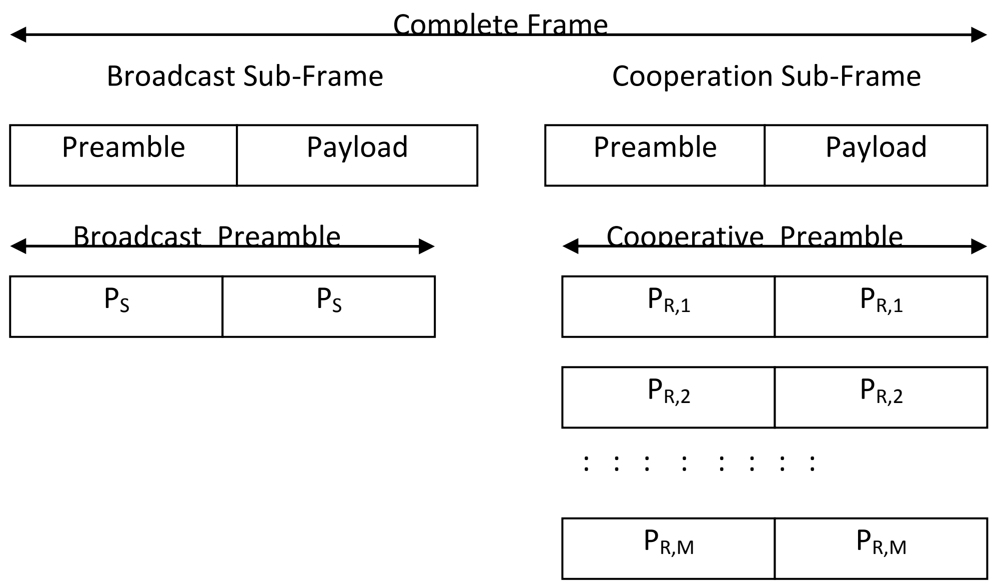

Figure 5.3: Frame Structure of CD-OFDM comprising broadcast and cooperative subframes. FD preamble for source and M relay nodes are also shown.

In B-phase, FDBP is composed of N_{pd} repeated FD training symbols $\{P_S[n]: 0 \leq n \leq N_u - 1\}$ from complementary golay (CG) sequence [33] . The index set of subcarriers assigned to P_S is $\mathbb{P}_S \subset \left\{\frac{-N_u}{2}, \frac{-N_u}{2} + 1, \dots \dots, \frac{N_u}{2}\right\}$. The cardinality of this set is $|\mathbb{P}_S| = N_u$. CAS mapped data block follows the FDBP.

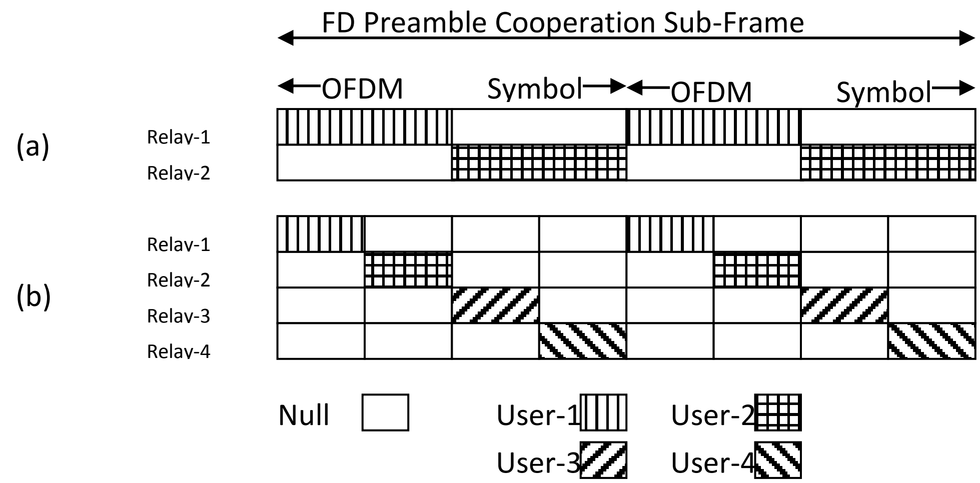

Figure 5.4: Frequency domain preamble patterns for two and four relays

(a) Two cooperating relays. (b) Four cooperating relays. Cyclic prefix is not shown here but actually used with every OFDM symbol.

In C-phase, index set of subcarriers assigned for q_{th} RN is $\mathbb{P}_{R,q}$ and depends on CAS. The FDCP of q_{th} node is unique and is formed by placing null on all subcarriers except those included in $\mathbb{P}_{R,q}$. Assuming M active nodes, the cardinality of index set for q_{th} RN is $\left|\mathbb{P}_{R,q}\right| = \frac{N_u}{M}$. Note that only those values of M are allowed that result in integer values for $\left|\mathbb{P}_{R,q}\right|$. In case of sub-band CAS with $M = 2$, index set for first relay is $\mathbb{P}_{R,1} = \left\{\frac{-N_u}{2}, \frac{-N_u}{2} + 1, \dots \dots, -1\right\}$ and index set for second relay is $\mathbb{P}_{R,2} = \left\{1,2, \dots \dots, \frac{N_u}{2}\right\}$. The FD training symbol of a specific RN (i.e. $P_{R,x}$) is formed by placing null at all subcarriers excluded from respective subset and placing respective CG sequence value on remaining active subcarriers.

$$P_{R,x}(l) = \begin{cases} P_S(l), & l \in \mathbb{P}_{R,x} \\ 0, & else \end{cases} \tag{67}$$

where

$$-\frac{N_u}{2} \leq l \leq \frac{N_u}{2}$$

Then IFFT operation is performed on this FD training symbol to get respective TD OFDM training symbol. Then N_{pd} periods of this TD OFDM training symbol constitute the complete TD preamble that is followed by data block. Each RN transmits its data on its pre-assigned subcarriers. Figure 5.4 shows FD preamble for two and four RN cooperating system.

The received signal during C-phase is a superposition of transmitted signals from all RNs. The unique preamble for each RN will allow us to separate the cooperating nodes at the destination end for CFO estimation and correction

5.6.3 CD-OFDM signal and Channel Model

A simplified block diagram for transmitter and receiver is shown in figure 5.5 that only shows system components necessary for explaining the proposed algorithm. In figure, dotted blocks are used only during cooperative phase. Whereas, shaded blocks show the CFO estimation and correction modules. In our model, we will consider the C-phase, where multiple RNs are transmitting simultaneously and this aggregate signal is received at DN.

All nodes are OFDM system using N point inverse fast fourier transform (IFFT). There are M RNs and each node transmits its signal independently on CAS mapped subcarriers. $a_{n,k}$ is null for non-assigned subcarriers. The complex baseband signal transmitted by x^{th} RN is described as:

$$s_x(t) = \frac{1}{\sqrt{T_u}} \sum_{n=-\infty}^{\infty} \sum_{k=\frac{N_u}{2}}^{\frac{N_u}{2}-1} a_{n,k}\, \psi_{n,k}(t) * g_T(\tau) \tag{68}$$

where $x = \{1,2, \dots, M\}$. The OFDM symbol length in a sample spaced system is $N_c = N_u + N_g$. Finally, the equivalent representation for the k samples of transmitted baseband n_{th} OFDM symbol $s_x(k)$ is as:

$$s_x(k) = \frac{1}{\sqrt{N}} \sum_{l=-\frac{N_u}{2}}^{\frac{N_u}{2}-1} a_{n,k}\, e^{j2\pi\left(\frac{k.l}{N}\right)} \qquad -N_g \le k \le N-1 \tag{69}$$

Consider a frequency selective multipath fading channel $h_x(\tau, t)$ that combines the effect of actual channel impulse response (CIR) and transmit filter $g_T(\tau)$.

$$h_x(\tau, t) = \sum_i h_{x,i}(t)\delta(\tau - \tau_i) \qquad i = 0,1, \dots \dots \dots . K_x - 1 \tag{70}$$

Note that $h_{x,i}(t)$ and τ_i are the complex path gain and delay at time t for link from x^{th} RN to DN. The maximum channel delay spread (MCDS) is $\tau_{max,x} = \tau_{i=K_x-1}$ and K_x is the length of channel impulse response for link from x^{th} RN to DN. For sample spaced channel, $\tau_i = i$ and h_i represents path delays and discrete-time channel impulse response respectively. Assuming a flat receive filter, the receiver input signal at DN (D) from single x^{th} RN is:

$$r_{D,x}(t) = \sum_i h_{x,i}(t) s_x(t - \tau_i) + w(t) \tag{71}$$

The equivalent representation for the k samples of received baseband n_{th} OFDM symbol is:

$$r_{D,x}(k) = \sum_{i=0}^{K_x-1} h_{x,i} s_x(k-\tau_i) + w(k) \tag{72}$$

where $w(k)$ is the sample of zero mean complex Gaussian noise process with variance σ_w^2. The geometric gain $G_{x,y}$ for x^{th} RN to SN or DN is as under [23]. SD indicates link from SN to DN.

$$G_{x,y} \stackrel{\text{def}}{=} \frac{E\{\sum_{i=0}^{K_{x,y}-1} |h_{x,i}|^2\}}{E\{\sum_{i=0}^{K_{SD}-1} |h_{SD}[i]|^2\}} \tag{73}$$

5.7 PROPOSED CARRIER FREQUENCY SYNCHRONIZATION METHOD

The CFO synchronization in a cooperative scenario is different from a single user case. First, all RNs are spatially separated and have separate oscillators with independent oscillator drifts. Second, all RNs have an independent channel path with different path delays. Third, all RNs transmit asynchronously unless there is a mechanism to ensure synchronous transmission. This problem is further exaggerated due to different path lengths for each RN to DN link. Fourth, all RNs transmit simultaneously by sharing time and frequency domain so user separation at destination is quite challenging. User separation is required for CFO estimation of each RN. Finally, even if somehow CFO estimation for each RN is successfully carried out then CFO correction at DN for one RN will introduce CFO in other RN signals. The proposed CFO estimation and correction method will take care of all these issues.

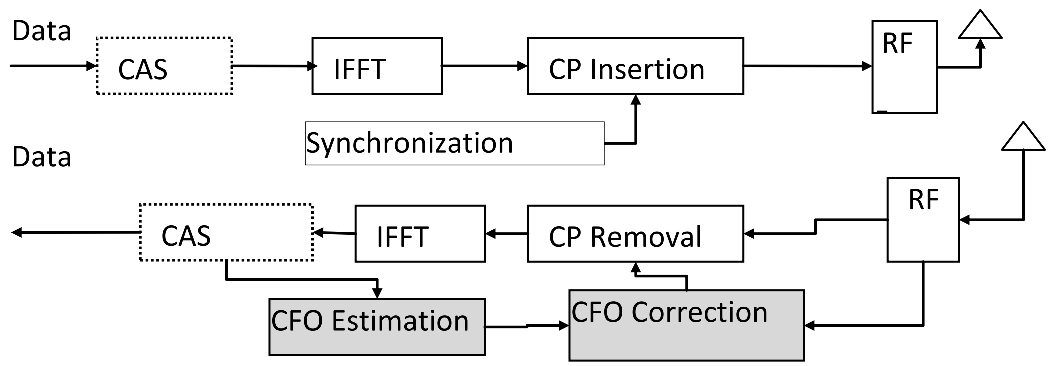

Figure 5.5: Block diagram of CD-OFDM transmitter and receiver.

In order to address the asynchronism problem, TO and CFO information from DN is fed back to SN and RNs for local synchronization. It eases the asynchronism and synchronization problem a bit. To further relieve the timing synchronization at DN, the CP length is extended to the extent that it accommodates the combined effect of the MCDS and maximum two-way propagation delay $\rho_{max} = \max\{\rho_x: x = 1,2,\dots,M\}$. It is accomplished by making $N_g \geq \tau_{max} + \rho_{max}$. Also, note that $\tau_{max} = \max\{\tau_{max,x}: x = 1,2,\dots,M\}$. Such a system is known as quasi-synchronous and timing errors can be handled as part of channel response.

5.7.1 Carrier Frequency Offset Estimation

At the DN, receiving antenna superimposes all RN signals to produce an aggregate signal that is represented in baseband as:

$$r_D(k) = \sum_{x=1}^{M} r_{D,x}(k) + w(k) \tag{74}$$

Taking symbol timing offset and carrier frequency offset into consideration, the received signal $r_{D,x}(k)$ for C-phase from x^{th} RN becomes:

$$r_{D,x}(k) = exp(j\varphi_x)\,.\,exp\,(j\frac{2\pi k\nu_x}{N})\sum_{i=0}^{K_x-1} h_{x,i}.\,s_x\big(k-\tau_{x,i}-\theta_x\big) \tag{75}$$

where ν_x is the carrier frequency normalized by the subcarrier spacing, θ_x is the integer timing error, φ_x is an arbitrary carrier phase factor , $h_{x,i}$ is a specific channel impulse response tap , $\tau_{x,i}$ is timing offset for x^{th} RN. Note that φ_x cannot be distinguished from phase shift introduced by channel and therefore is assumed to be absorbed in channel effect and subsequently compensated by channel estimation module.

We are only dealing with CFO synchronization problem so it is assumed that system is already time synchronized.

$$r_{D,x}(k) = exp\,(j\frac{2\pi k\nu_x}{N})\sum_{i=0}^{K_x-1} h_{x,i}.\,s_x\big(k-\tau_{x,i}\big) \tag{76}$$

Note that noise contribution from each RN is already incorporated in $r_{D,x}(k)$. The CFO estimation is based on a N_{pd} times repeated FD preamble that is unique for each RN.

It is assumed that channel remains constant for N_{pd} OFDM symbol duration. For sake of brevity, $N_{pd} = 2$ is used but can be extended to any length by incorporating minor changes in derivations that follow. Increasing N_{pd} will increase the overhead but will improve the estimation because of averaging effect. Due to extended CP, the received samples placed in the DFT window are free from ICI and two repeated training symbols $r_{D,x}^{(0)}(k)$ and $r_{D,x}^{(1)}(k)$ received for x^{th} RN are:

$$r_{D,x}^{(0)}(k) = \exp\left(j\frac{2\pi k\nu_x}{N}\right)\sum_{i=0}^{K_x-1} h_{x,i}.s_x(k) \tag{77}$$

$$r_{D,x}^{(1)}(k) = \exp\left(j\frac{2\pi k\nu_x}{N} + j\frac{2\pi N_c\nu_x}{N}\right).\sum_{i=0}^{K_x-1} h_{x,i}.s_x(k) \tag{78}$$

After FFT, for AWGN channel, aggregate received repeated symbols $R_D^{(0)}(k)$ and $R_D^{(1)}(k)$ are:

$$R_D^{(0)}(l) = P_S^{(0)}(l) \tag{79}$$

$$R_D^{(1)}(l) = P_S^{(1)}(l).exp\,(j\frac{2\pi N_c\nu_x}{N}) \tag{80}$$

Note that after FFT, the subcarrier index l is used instead of k. Now FD training subcarriers for each RN can be easily separated, as their respective subcarrier index sets are known. $P_S^{(0)}(l)$ and $P_S^{(1)}(l)$ are received repeated composite preamble symbols with added noise and in case of noise free channel both are equal.

$$R_{D,x}^{(0)}(l) = P_{R,x}^{(0)}(l) + noise \tag{81}$$

$$R_{D,x}^{(1)}(l) = P_{R,x}^{(1)}(l).exp\,(j\frac{2\pi N_c\nu_x}{N}) + noise \tag{82}$$

Now first and second received training symbol of a specific RN (i.e. $P_{R,x}^{(0)}(l)$ and $P_{R,x}^{(1)}$)are separated from the composite preamble as:

$$P_{R,x}^{(0)}(l) = \begin{cases} P_S^{(0)}(l), & l \in \mathbb{P}_{R,x} \\ 0, & else \end{cases} \tag{83}$$

$$P_{R,x}^{(1)}(l) = \begin{cases} P_S^{(1)}(l), & l \in \mathbb{P}_{R,x} \\ 0, & else \end{cases} \tag{84}$$

where $-\frac{N_u}{2} \leq l \leq \frac{N_u}{2}$

All null values are excluded and $\frac{N_u}{M}$ subcarrier values from each repeated training symbol (i.e. $\breve{P}_{R,x}^{(0)}(i)$ and $\breve{P}_{R,x}^{(1)}(i)$) are used for CFO estimation. For a specific RN, it is evident that two repeated portions are affected in a same way by channel and the only difference between their respective values is $\frac{2\pi N_c v_x}{N}$. This difference expression is further simplified when $N_c = N$. This fact makes it possible to estimate the CFO of each RN in cooperative scenario in a way similar to single user estimation [36]. The estimated CFO $\hat{v}_x$ for each RN can be calculated as:

$$\hat{v}_x = \frac{1}{2\pi \frac{N_c}{N}} tan^{-1} \left\{ \frac{\sum_{i=1}^{\frac{N_u}{M}} \mathfrak{Im}[Q_{x,i}]}{\sum_{i=1}^{\frac{N_u}{M}} \mathfrak{Re}[Q_{x,i}]} \right\} \tag{85}$$

$$Q_{x,i} = \breve{P}_{R,x}^{(1)}(i).conj\{\breve{P}_{R,x}^{(0)}(i)\} \tag{86}$$

where $1 \leq i \leq \frac{N_u}{M}$

5.7.2 Carrier Frequency Offset Correction

CFO estimate $\hat{v}_x$ for each RN is obtained by using the proposed method but CFO correction cannot be directly applied to the aggregate signal. Let $R_{R,x}^{(n)}(l)$ be the n^{th} received information symbol in FD that is formed by placing null at the subcarriers not included in index set of x^{th} RN. Placement of nulls on non-member subcarriers results in noise suppression because originally no information was transmitted on those subcarriers by x^{th} RN.

where
$$R_{R,x}^{(n)}(l) = \begin{cases} C_{R,x}^{(n)}(l), & l \in \mathbb{P}_{R,x} \\ 0, & else \end{cases} \qquad 2 \leq n \leq data\ block\ size \tag{87}$$

Now take IFFT of $P_{R,x}^{(n)}(l)$ and then apply CFO correction using $\hat{v}_x$ to this TD signal $r_{D,x}^{(n)}(l)$ as: Same procedure is repeated in parallel for all RNs.

$$r_{D,x}^{(n)}(l) = IFFT\{P_{R,x}^{(n)}(l)\}.exp\,(-j\frac{2\pi l\hat{v}_x}{N}) \tag{88}$$

5.8 PERFORMANCE EVALUATION, SIMULATION RESULTS AND DISCUSSION

The performance of proposed algorithms is evaluated through computer simulations. The FD preamble is composed of two (i.e. $N_{pd} = 2$) repeated OFDM symbols. GC sequence of length N is used for forming training symbol. The proposed preamble exhibits good peak to average power ratio (PAPR).

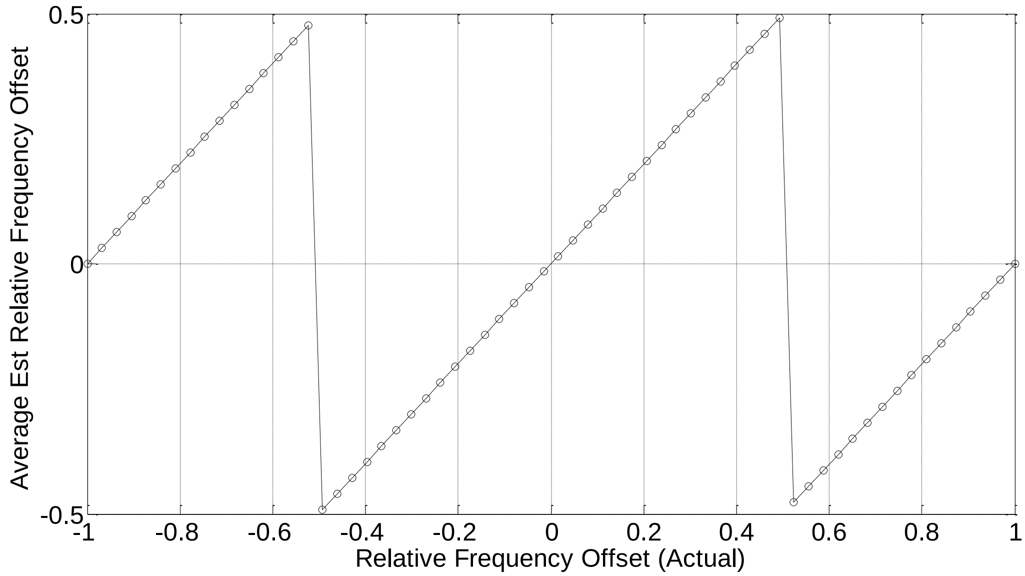

Figure 5.6: Average CFO estimate using proposed estimator versus actual CFO.

The cooperative diversity network comprises of one SN, two RNs (i.e. $M = 2$) and one DN. Geometric gain G_l of 0dB is used for all considered cases for fair comparison. All nodes are OFDM based systems with 1024 subcarrier and 10% guard interval. QPSK is used for baseband modulation. All simulations are run atleast 10,000 times in baseband and no pulse shaping or frequency up-conversion is done. The normalized CFO is restricted to less than half of the carrier spacing. The AWGN and Rayleigh channel with three taps is used for simulation. For performance comparison (figure 5.11) with other well-known algorithms, some of the parameters were modified for tractable and fair comparison.

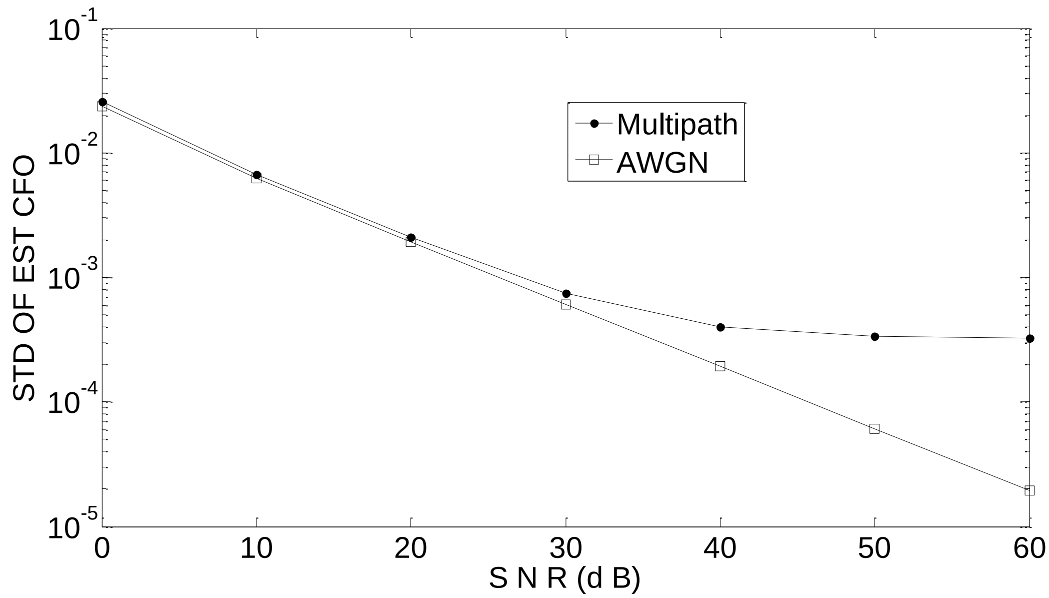

Figure 5.7: Standard deviation of estimated CFO versus SNR

In figure 5.6, average of estimated CFO $E\{\hat{\nu}_x\}$ calculated by using the proposed estimator is plotted against actual relative CFO for 20dB SNR in AWGN channel. Plot shows that proposed estimator accurately estimates the actual CFO and there is no ambiguity in half carrier spacing range.

In figure 5.7, standard deviation (STD) of estimated CFO $\hat{\nu}_x$ is plotted versus SNR for AWGN and multipath channel. STD hits a floor in case of multipath due to dispersive nature of the channel. Note that proposed estimator was actually derived for AWGN but has shown comparable performance for multipath in practical SNR range.

In figure 5.8, variance of estimated CFO is plotted against different values of actual CFO. Results show that variance remains constant for different CFO values for single user and two-user case. Variance only shoots up when we approach the half carrier spacing limit.

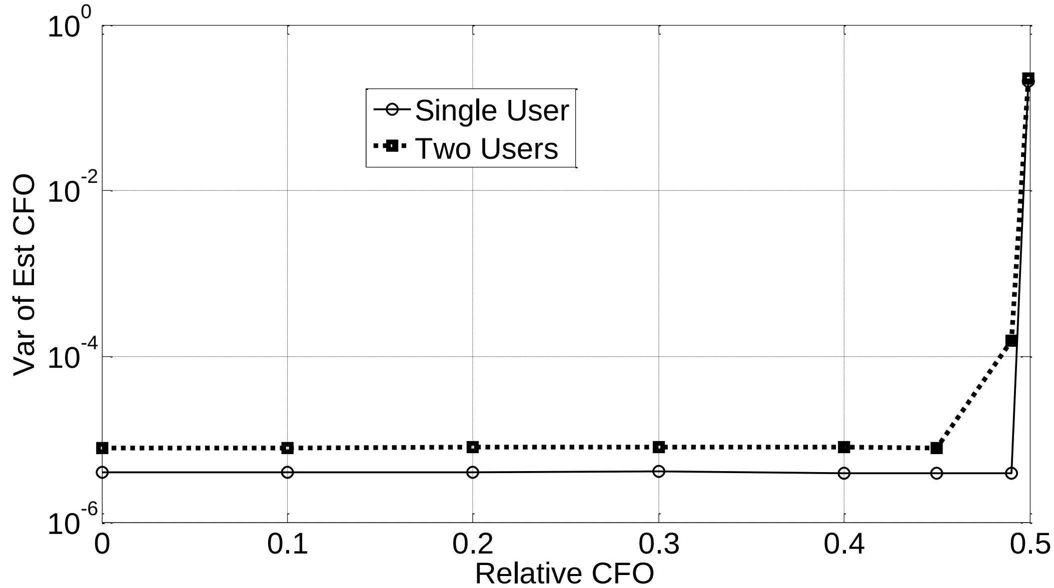

Figure 5.8: Variance of estimated CFO versus actual CFO for single user and two cooperating relay nodes in AWGN environment (20 dB).

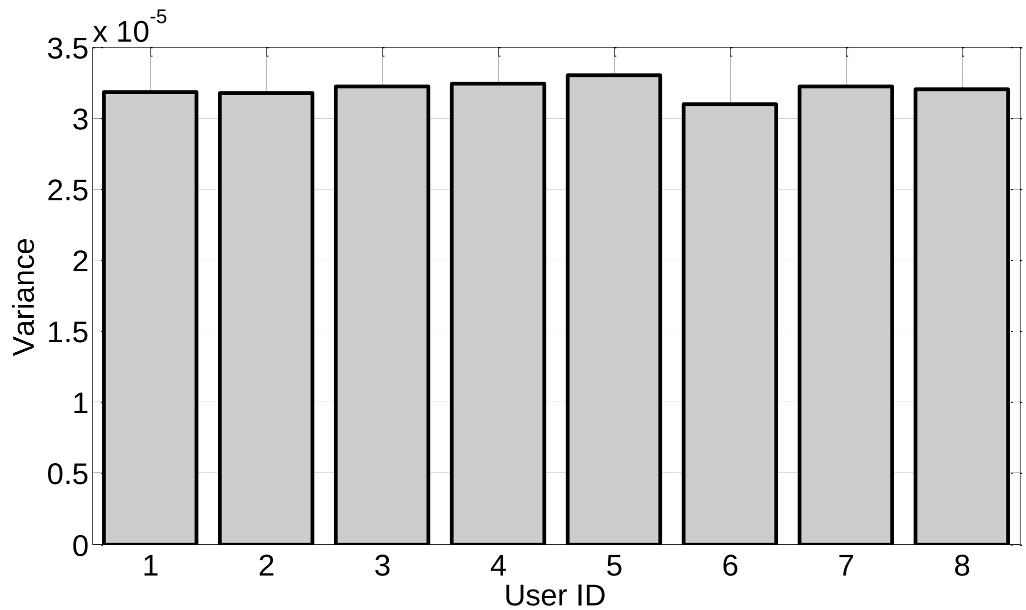

Figure 5.9: Variance of estimated CFO versus increasing number of cooperating relay nodes in AWGN environment (20 dB).

Figure 5.9 shows the effect of increasing number of RNs on estimator variance. Remarkably, variance almost remains constant when number of RNs in a cooperating environment is increased from one to eight.

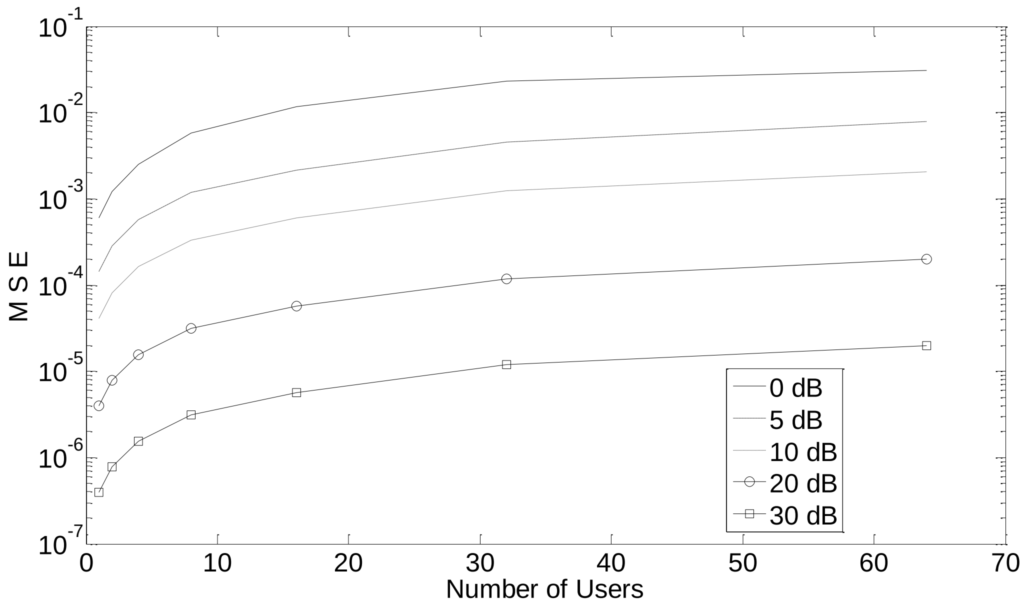

Figure 5.10: Mean square error of estimator versus different number of cooperating RNs in AWGN channel.

Figure 5.10 shows the effect of change in total number of cooperating RNs on mean squared error (mse) of proposed estimator. Mean squared error increases as the number of RNs is increased from one to twenty RNs but thereon becomes steady. Similarly, mse increases with decrease in SNR value.

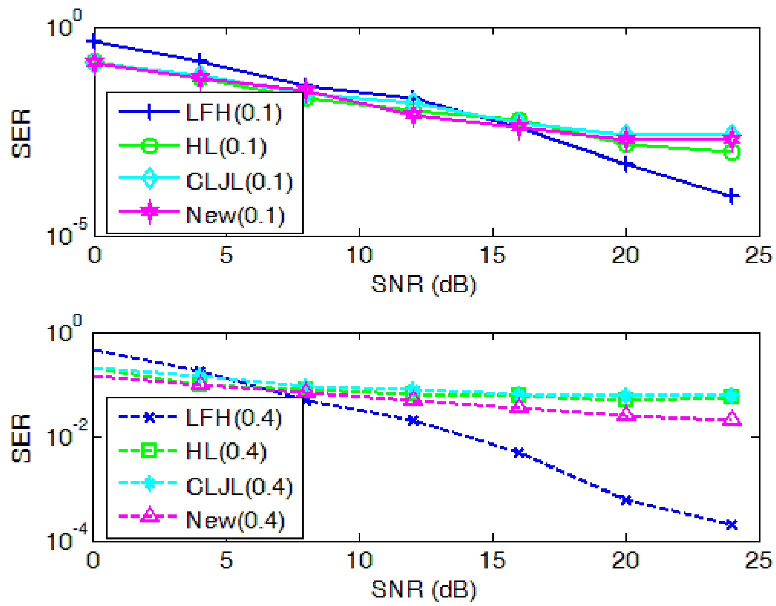

Figure 5.11: Symbol error rate versus SNR for different carrier frequency offset estimators in cooperative environment.

In figure 5.11, the performance of proposed algorithm (i.e. "New") is compared with "HL" [55], "LFH" [50] and "CLJL" [47] in terms of symbol error rate (SER). The FFT size of 64 is used and accurate time synchronization is assumed where applicable for concentrating on performance of CFO algorithms. All algorithms were modified to exclude convolutional coding and incorporate Alamouti STBC. For fair comparison, the HL algorithm was constrained to single iteration only. Reason being that HL algorithm takes its initial estimate from CLJL algorithm for iteration so increasing number of iterations may favour it out of proportion. Moreover, even single iteration HL is computationally more costly as compared to other algorithms. However, for sake of completeness, HL algorithm was run for four iterations (result not shown in figure 5.11) and significant observation was an improvement in performance for HL(0.4) and it converged towards HL(0.1). Increase in iterations resulted in slight improvement for HL(0.1). Moreover, different bandwidth efficiency of these algorithms was compensated by altering the transmission power. Figure 5.11 shows that proposed algorithm “New(0.1)” performs better than other algorithms in the practical SNR values (i.e. 12~18 dB) for average normalized CFO value of 0.1. Even for the case of higher CFO value of 0.4, the “New(0.4)” algorithm performs better than “HL” and “CLJL” , specially at large SNR values. The performance of “LFH” is understandably better for higher SNR and especially for high CFO values owing to larger CP and computational complexity. However, it is included in comparison for the purpose of completeness.

5.9 CHAPTER SUMMARY

The OFDM and MIMO technologies have been successfully used in a number of wireless standards to provide high data rate in a multipath fading environment. However, in mobile communications, it is not feasible to have multiple antennas at the user end. In such scenario, cooperative diversity systems may be considered as an attractive alternative. CD-OFDM systems may be widely adopted in future mobile communication systems due to their favorable features. In a step towards that direction, this paper presented and evaluated performance of a FD preamble that especially suites CD-OFDM systems using DnF relay protocol. Moreover, CFO estimation algorithm and CFO correction method are also described and performance evaluated. Simulations verify that proposed estimation algorithm shows good results in terms of mean square error, variance of estimator and symbol error rate. Proposed algorithm effectively uses separate training for each relay and is bandwidth efficient as compared to [50] and much less computationally intensive as compared to [47], [48], [49], [50], [51] and [52].

CHAPTER 6

FINE TIMING SYNCHRONIZATION FOR CD-OFDM SYSTEM

6.1 INTRODUCTION

Many papers have shown that performance benefits attributed to MIMO are realizable by using cooperative diversity systems but mostly same timing and carrier frequency offset for participating nodes are assumed for such studies [12]. However, these assumptions are not valid in practical scenario because nodes do not share the same channel and oscillator. CD-OFDM system using space-time coding is more vulnerable to timing and channel estimation errors. In case of synchronization errors, CD-OFDM system gets a performance degradation penalty instead of performance improvement [13], [14], [22] and [51].

6.2 CONTRIBUTION

This chapter develops a general framework for estimating fine timing alongwith CIR for DnF mode cooperative relay system that is published in [18]. All synchronization and estimation processing is done in time domain (TD) to circumvent multiple FFT operations. It results in a low complexity algorithm because same TD correlation is utilized to estimate timing and CIR [54] and [53]. The proposed algorithms do not assume any synchronism between participating nodes and is equally good for asynchronous cooperative nodes. A Block diagram of the system used for algorithm development is shown in figure 6.1.

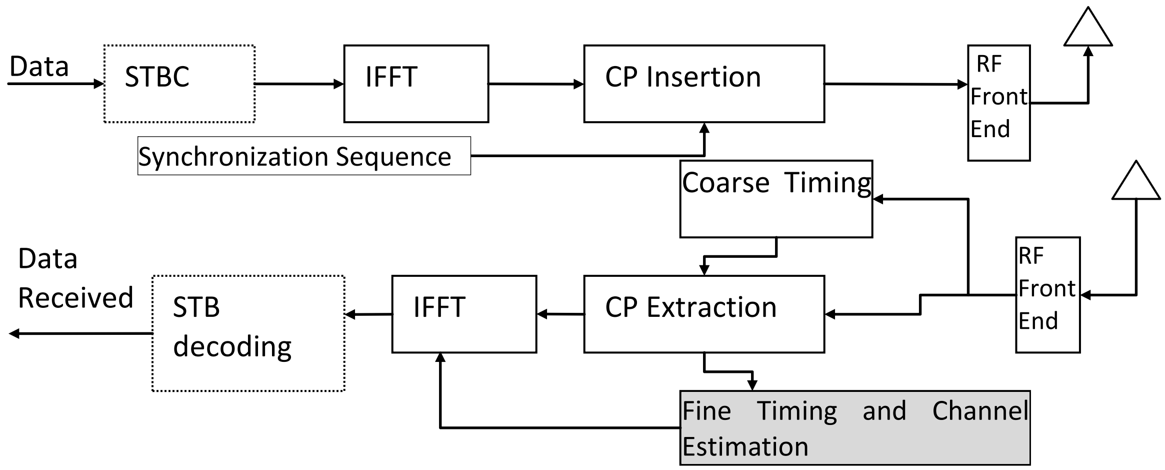

Figure 6.1: Block diagram of CD-OFDM transmitter and receiver. STBC/STB decoding modules are used only during cooperative phase.

6.3 CHAPTER ORGANIZATION

The chapter is organized in separate sections for clarity. Section 6.4 introduces the CD-OFDM system for DnF mode. Fine timing synchronization and channel estimation method are elaborated in section 6.5 and section 6.6 respectively. Section 6.7 presents the simulation results to validate the proposed algorithms.

--Notations: Small letters represent TD signals and capital letters shows the frequency domain (FD) signals. The node (x) represents source(S), relay(R) or destination(D). The transmission phase (y) represents the listening (L) or cooperation (C) phase. Link (l) from source to relay, source to destination and relay to destination are shown by SR, SD and RD symbols, respectively. * denotes convolution operation.

6.4 SYSTEM MODEL AND DESCRIPTION

6.4.1 Frame Structure, Preamble and Space Time Cooperation Architecture

CD-OFDM frame comprises of two subframes: listening subframe and cooperation subframe [23], [11]. The length of these subframes does not need to be equal. Each subframe comprises of data and a FD preamble. Frame structure, preamble and space-time coding architecture are the same as explained in previous chapters and reported in [16]. The preamble for source and relay during C- phase is shown in Figure 6.2. First preamble symbol is independent and second is orthogonal.

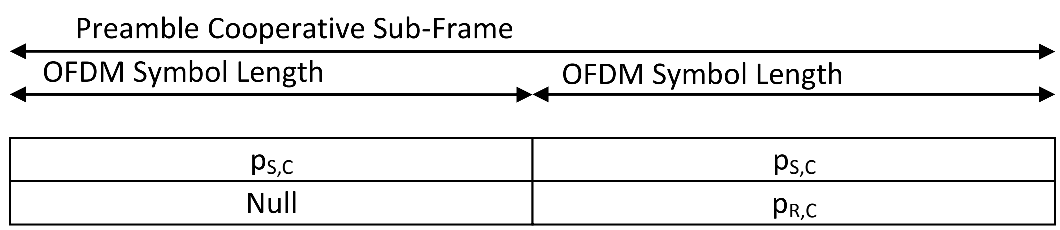

Figure 6.2: p_{SC} and p_{RC} are preferred pair gold sequences for cooperative phase preamble of source and relay respectively.

6.5 PROPOSED SYNCHRONIZATION METHOD

Timing synchronization is completed in two steps: coarse timing [16] and fine timing because it allows early signal acquisition in burst mode transmission [56]. Timing synchronization during listening phase is similar to any other OFDM system. However, in C- phase, synchronization becomes a bit different due to inter node interference. It is considered that signal of interest is deteriorated by timing and frequency offset. Thus, signal $r_{xy}(k)$ received at node $(x = R \ or \ D)$ for listening phase$(y = L)$ becomes:

$$r_{xL}(k) = exp(j\varphi_l) \,.\, exp\,(j\frac{2\pi k v_l}{N}) \sum_{i=0}^{K-1} h_{l,i}.\, s_l\big(k - \tau_{l,i}\big) + w(k) \qquad (89)$$

and received signal for cooperation phase at destination is:

$$\begin{aligned} r_{DC}(k) = {} & exp(j\varphi_{SD})\, exp\,(j\frac{2\pi k v_{SD}}{N}) \sum_{i=0}^{K-1} h_{SD,i}.\, s_{SD}\big(k - \tau_{SD,i}\big) \\ & + exp(j\varphi_{RD}).\, exp\,(j\frac{2\pi k v_{RD}}{N}) \sum_{i=0}^{K-1} h_{RD,i}.\, s_{RD}\big(k \\ & - \tau_{RD,i} - \rho\big) + w(k) \end{aligned} \qquad (90)$$

where v_l is the carrier frequency normalized by the subcarrier spacing , φ_l is an arbitrary carrier phase factor , $h_{l,i}$ is a specific CIR tap , $\tau_{l,i}$ is timing offset and ρ is timing offset between received signal from source and relay. It is assumed that CP is larger than the combined length of τ_{max} and ρ.

6.5.1 Fine Timing Synchronization Algorithm

Fine timing synchronization utilizes the TD correlation of received signal and the known preamble to identify the first channel tap. It is assumed that correlation start always includes the exact frame start so that first channel tap is not missed in correlation result. This assumption is justifiable because coarse timing is advanced to ensure it. Note that correlation operation starting from time-advanced coarse timing will result in preceding nulls (near zero correlation values) followed by CIR taps. The channel taps will shift on time axis due to time varying nature of channel and same shift will be depicted in correlation results. Thus accurate symbol timing estimation even in time varying channel is possible. This shift in channel taps is used to fine-tune the coarse timing estimate.

Many methods are described in the literature for finding the location of first actual channel tap [31], [28] but in this chapter a simple method based on finding maximum energy tap is used. This method takes advantage of the fact that in OFDM systems due to the presence of CP, a timing estimate that lies in ISI (Inter Symbol Interference) free region of CP will not degrade the performance. The correlation $R_{r_{xy},p_{xy}}$ of received signal with known TD preamble is:

$$R_{r_{xy},p_{xy}}(d) = \frac{1}{N}\sum_{i=0}^{N_{pre}-1} r_{xy}(d).\,p_{xy}^{*}(d-i) \tag{91}$$

In order to limit the search length, correlation is computed from $d = \hat{d}_{coarse}$. During cooperation phase, CD-hybrid (as described in chapter 2) frame is used so a special timing metric is proposed that fully exploits the structure of this preamble. Fine timing metric for SD and RD link during cooperation phase are:

$$\gamma_{fine,SD} = R_{r_{DC},p_{SC}}(\hat{d}_{coarse}) \tag{92}$$
$$\gamma_{fine,RD} = R_{r_{DC},p_{RC}}(\hat{d}_{coarse} + N) \tag{93}$$
$$\hat{d}_{fine,SD} = arg_{d}^{max}\{\gamma_{fine,SD} \mid \gamma_{fine,SD}(d) \geq \gamma_{th,fine}\} \tag{94}$$
$$\hat{d}_{fine,RD} = arg_{d}^{max}\{\gamma_{fine,RD} \mid \gamma_{fine,RD}(d) \geq \gamma_{th,fine}\} \tag{95}$$
$$\hat{d}_{fine} = \hat{d}_{fine,SD} + \hat{d}_{fine,RD} - N - d_{fine,adv} \tag{96}$$

where $\gamma_{th,fine}$ and $d_{fine,adv}$ are fine timing threshold and fine timing pre-advance. In this work, same $\gamma_{th,fine}$ is used for SD and RD link but it is possible to use different threshold for each link depending on channel characteristics. It is assumed that first channel tap is the maximum energy tap. CD-hybrid preamble allows determining the frame start for SD (i.e. $\gamma_{fine,SD}$) and RD (i.e. $\gamma_{fine,RD}$) separately that is subsequently used to determine the frame start for combined signal

Fine timing metric for listening phase is simple because of the repetitive structure of preamble used in listening phase. In this case, correlation $R_{r_{xy},p_{xy}}$is averaged over two periods. It results in an improved performance due to the quasi-static channel assumption. The averaged correlation result is then used to form the timing metric and subsequently fine timing is determined independently at relay and destination.

6.6 CHANNEL ESTIMATION ALGORITHM

The wireless CIR of each link is modeled as tapped delay line with sample spaced tap delays. In order to model channel as a wide sense stationary process (WSS) the channel taps are assumed to be uncorrelated with each other. Further, average energy of the total channel is normalized to one and delays τ_i are assumed constant for time of interest (i.e. two OFDM symbols). The received signal at destination during cooperation phase is superposition of SD and RD link signals. It is assumed that CIR for SD and RD links is statistically uncorrelated thus enabling the system to harness diversity gain. Thus complex CIR for SD and SR links during listening phase is:

$$h_{SD}(i) = \sum_i h_{SD,i}\delta(t-\tau_i) \tag{97}$$

$$h_{RD}(i) = \sum_i h_{RD,i}\delta(t-\tau_i) \tag{98}$$

$$i = 0,1, \dots \dots \dots . K_l - 1$$

It is assumed that channel length for all links is equal i.e. K_l=$K_{SD} = K_{RD}$. The TD preamble and correlation result used for fine timing synchronization can also be used for calculating the CIR. The received signal during listening phase at destination (D) and relay(R) are:

$$r_{D,L}(k) = s_S(k) * h_{SD}(i) + noise \quad (99)$$
$$r_{R,L}(k) = s_S(k) * h_{SR}(i) + noise \quad (100)$$

The samples of first preamble symbol $r_{D,C}^{(0)}(k)$ and second preamble symbol $r_{D,C}^{(1)}(k)$ received during cooperation phase at destination (D) are:

$$r_{D,C}^{(0)}(k) = s_S(k) * h_{SD}(i) + noise \quad (101)$$
$$r_{D,C}^{(1)}(k) = s_S(k) * h_{SD}(i) + s_R(k) * h_{RD}(i) + noise \quad (102)$$

Note that structure of CD-Hybrid preamble during cooperation phase can be used to estimate $r_{D,C}^{(2)}(k)$ that is the samples of second preamble symbol in absence of interference from source. The estimation of $r_{D,C}^{(2)}(k)$ is valid based on the assumption of linear superimposition of relay and source signals in a quasi-static channel.

$$r_{D,C}^{(2)}(k) = r_{D,C}^{(1)}(k) - r_{D,C}^{(0)}(k) + noise \quad (103)$$

where $i = 0,1, \dots \dots \dots . K_l - 1$
$0 \leq k \leq N - 1$

In listening phase, estimated CIR for SD and SR links can be found by taking cross correlation of received signal $r_{D,L}(k)$ and $r_{R,L}(k)$ respectively with known TD preamble and averaging the same over two periods because of repetitive pattern of preamble. In order to reduce complexity, correlation results of fine timing module are used for CIR estimation so coarse symbol start is used for initiating cross correlation operation. Finally estimated CIR for SD and SR link in listening phase is:

$$\hat{h}_l(i) = \frac{R^{trunc}{}_{r_{xy},p_{xy}}(i)}{max\ (|R^{trunc}{}_{r_{xy},p_{xy}}(i)|)} \qquad (104)$$

where $i = 0,1, \dots \dots \dots . K_l - 1$

Note that $R^{trunc}{}_{r_{x,y},P_{xy}}$ is the truncated version of $R_{r_{xy},p_{xy}}$ in accordance with maximum channel length.

In cooperation phase, correlation of $r_{D,C}^{(0)}(k)$ and $r_{D,C}^{(2)}(k)$ with respective preamble is used to estimate the SD and RD CIR by using (104). In order to evaluate performance of CIR estimator during C- phase, Normalized Mean Square Error (NMSE) is defined as:

$$NMSE = \sum_{i=0}^{K_l-1} \left|\frac{h_{SD}(i) - \hat{h}_{SD}(i)}{h_{SD}(i)}\right|^2 + \left|\frac{h_{RD}(i) - \hat{h}_{RD}(i)}{h_{RD}(i)}\right|^2 \qquad (105)$$

6.7 PERFORMANCE EVALUATION, SIMULATION RESULTS AND DISCUSSION

The performance of proposed algorithms is evaluated through computer simulations. The cooperative diversity network comprises of one source, relay and destination node each. All nodes are OFDM based systems using QPSK modulation. All simulations are run in baseband and no pulse shaping or frequency up-conversion is done. For fair comparison, a 1024 subcarrier OFDM system with 10% guard interval is used.

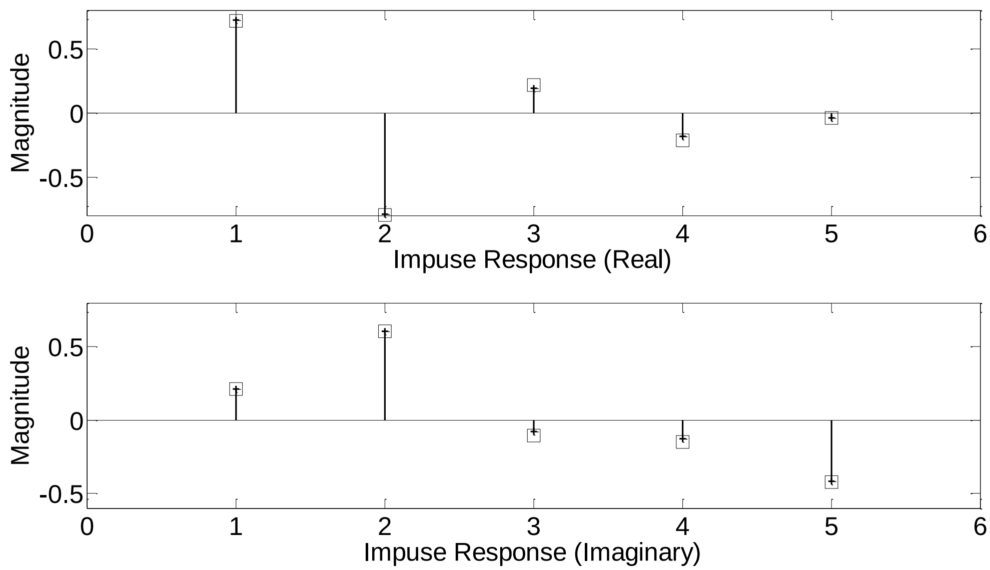

Figure 6.3: Channel Impulse Response estimated using time domain preamble for SD Link during listening phase (20 dB).

In Figure 6.3, CIR for a five taps Rayleigh channel is estimated. Note that an exact Impulse response value lies at the middle of box while a crosshair (+) shows the estimated impulse response value. It is evident that channel estimator reliably estimates the impulse response for practical SNR case.

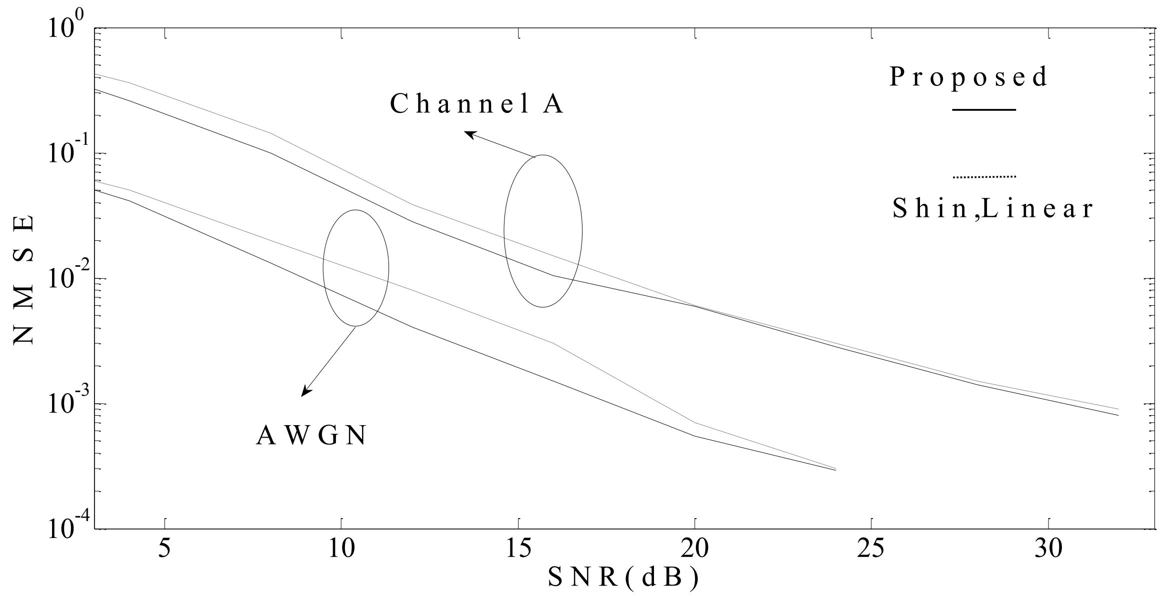

Figure 6.4: NMSE for channel estimate in cooperation phase.

Figure 6.4 shows normalized mean square error (NMSE) of channel estimate in C- phase compared with Shin [23]. The proposed algorithm performs better than Shin primarily at low SNR due to two reasons. First, it is based on orthogonal and independent structure of preamble. Second, Shin uses interpolation for estimating intermediate taps and error margin is larger at low SNR.

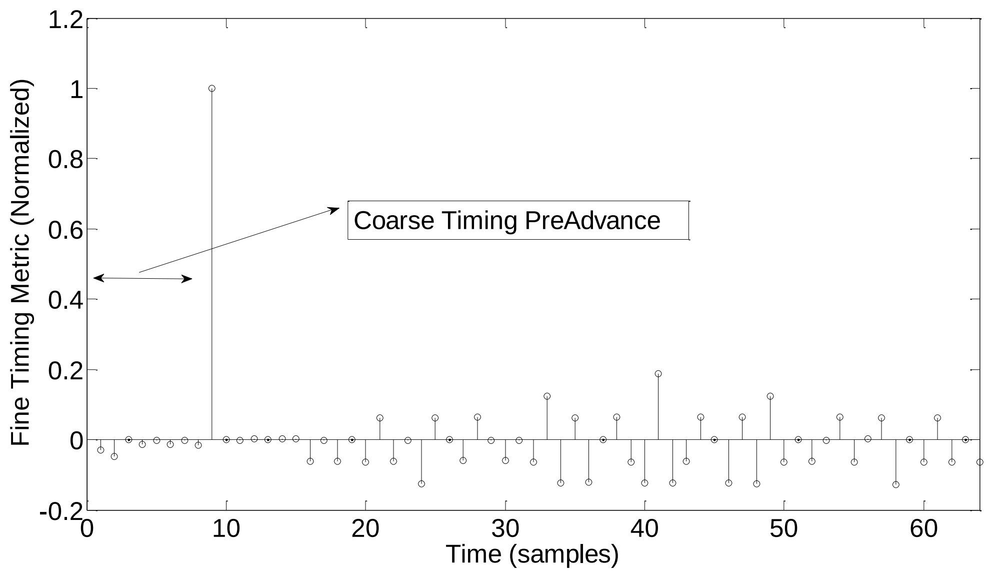

Figure 6.5: Fine Timing Metric (Normalized) for listening phase (20 dB) in AWGN channel.

Figure 6.5 shows the fine timing metric for SD link of listening phase as recovered from CIR estimate in case of AWGN channel. Exact Frame start is recovered. Effect of coarse timing advance results in leading nulls which will be taken into consideration while determining the exact start of frame.

Finally, Figure 6.6 compares the mean square error (mse) performance of fine timing synchronizer with other published estimators like Minn [28], Czylwink [57] and Park [58]. It can be seen that proposed method gives almost constant mse after 7 dB. A constant mse for different SNR values makes synchronization process robust.

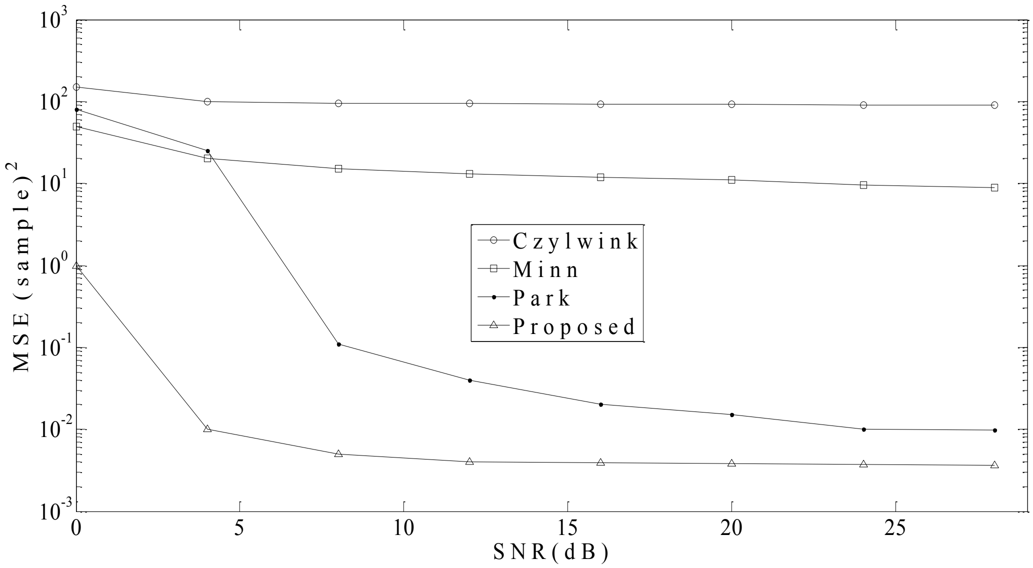

Figure 6.6: Mean square error comparison for fine timing synchronizer.

6.8 CHAPTER SUMMARY

In this chapter, two estimators are proposed for calculating fine timing and channel impulse response (CIR) of a CD-OFDM based communication system. The proposed low complexity algorithms are designed to operate with asynchronous nodes having independent timing and carrier frequency offsets. These algorithms fully exploit the specially designed structure of time domain preamble used for cooperative communications. For the sake of reducing complexity, both estimators use the correlation results of the same preamble. Moreover, CIR is estimated in time domain thus making multiple FFT operations redundant. Further, fine timing estimator is based on a simple but robust idea of first channel tap identification in cooperative communications scenario. The performance of these algorithms is evaluated in Rayleigh fading environment using Monte Carlo simulations and performance is found better than other comparable algorithms.

The proposed channel estimation algorithm performs better than Shin at low SNR. Similarly, proposed fine timing estimator is robust and gives better performance than [28], [57] and [58].

CHAPTER 7

CONCLUSION

7.1 INTRODUCTION

This research endeavor has two main objectives. First aim was to identify a research problem and contribute towards its solution. Second aim was to stimulate further research by exposing new research directions. A focused effort was made to achieve these objectives and the research work reported in this dissertation substantiates this claim.

7.2 THESIS SUMMARY

The research and development of communications technology is primarily driven by needs of military and commercial users. In general, both communities desired for higher throughput and mobility. In this work, OFDM is identified as pivotal technology for future wireless communication systems owing to its simple implementation in multipath channel. Integration of OFDM with other technologies is considered to further enhance the robustness, reliability, throughput and coverage area. In this context, technologies and concepts like MIMO, OFDMA, STBC and cooperative diversity are explored to develop an improved communication system that is referred as CD-OFDM in this dissertation.

It was observed that performance of CD-OFDM is heavily dependent on the quality of synchronization. Thereon, the synchronization problem of CD-OFDM is attacked and solutions proposed. This work is unique in its scope because instead of looking OFDM synchronization in isolation, an effort is made to address the synchronization issue in a scenario where OFDM is integrated with other technologies.

The CD-OFDM system, considered in this work, is a conglomerate of technologies like OFDMA, STBC and relays. The constituent technologies may vary depending on user requirement but all combinations are OFDM centric.

In chapter 4, CD-OFDM system uses relays and STBC. DnF Relays are used to incorporate cooperative diversity concepts and harness its inherent advantages like increased coverage area. STBC accrues diversity gain but requires accurate timing synchronization to use simple ML decoder. A preamble is presented that is tailor made to suite the requirements of this cooperative diversity system. Further, a coarse timing offset estimation algorithm is proposed for this scenario. Two low complexity variants are also described. Performance of these algorithms is evaluated and found to surpass some of the reference algorithms in literature.

In chapter 5, CD-OFDM system similar to OFDMA uplink was considered. Transmission protocol and frame structure for this system was developed and elaborated. Synchronization problem of OFDMA uplink transforms into a multiple parameter estimation problem and highly complex iterative algorithms are generally used to solve it. It is pertinent to mention that CFO estimation and compensation in OFDMA uplink requires user separation. Without user separation, CFO can neither be estimated nor compensated accurately. A simple CFO estimation algorithm and CFO compensation algorithm is proposed and evaluated.

Chapter 6 describes a fine-timing estimation algorithm for CD-OFDM scenario. Channel estimation is generally required for most of the modern communication systems. The proposed fine-timing algorithm utilizes the same channel estimate to determine the dominant channel path in a CD-OFDM system.

7.3 Future Work

In case of cooperative diversity systems including CD-OFDM, there is an inherent timing asynchronism in signals arriving from participating nodes due to diverse channel between any two nodes. The timing synchronization problem is the most challenging one and is addressed in case of CD-OFDM by increasing the CP to make the channel quasi-synchronous. However, increasing CP increases overhead and this loss becomes too costly when inter node distance is increased beyond 20km because CP almost becomes equal to frame length. In published literature, no efficient and practical method other than “quasi-synchronous assumption” exists. The asynchronism of cooperating nodes is a challenging research problem and warrants a novel and ingenious solution that may provide impetus to new more efficient MAN standards.

Moreover, during this research initiative different training preambles and cooperative diversity protocols were presented during evaluation of timing and CFO estimation algorithms. These preamble structures and transmission protocols have a definite impact on system throughput however; emphasis was deliberately focused on evaluation of performance of proposed estimators to keep the research problem manageable. It is felt that elaborate capacity analysis must be carried out in future to substantiate the case for practical utility of proposed system and estimators.

Furthermore, performance of proposed estimators is compared with numerous published estimators of same kind based on mean square error, variance and bit error rate. In general, comments were made regarding scale of complexity of these estimators but it would be a good idea to carry out detailed complexity analysis of these estimators.

APPENDIX-A

CASE STUDY - OFDM DESIGN PROCEDURE

In this case study, detailed procedure of OFDM design is discussed. First, user requirements are mentioned and then an appropriate design is gradually developed. The user wants to transmit 30 voice channels in hilly terrain. Assuming PCM quantization and A-law codec, single voice channel requires 64Kbps. The hilly terrain will have maximum path loss and will reduce the coverage area for a given transmission power. In this design as we are not concentrating on transmission power, so path loss factor of terrain will have no impact. SUI-5 channel model is used as true representation of our channel [59]. According to SUI-5 model, the expected maximum channel delay spread is : $\tau_{max} = 10\mu sec$.

In order to mitigate the dispersive nature of channel, CP must be greater than τ_{max}. We choose CP length: $T_G = 12\mu sec$. All multipath will fall within same bin so we do not need to resolve the multipath.

Overall transmission rate is 1.92Mbps. However, channel is frequency selective and channel coherence BW is $12KHz$. It can support maximum 20Kbps in case of single carrier system. When data rate will increase beyond 20Kbps, ISI will result and complex equalization process will be required. Therefore, it is advisable to use OFDM system in this case.

In OFDM design, it is assumed that CP is one eighth of the OFDM symbol duration T. Now the OFDM symbol duration is: $T = 96\mu sec$.

Carrier spacing f_Δ is related to symbol duration as: $f_\Delta = \frac{1}{T}$. It makes $f_\Delta = 10KHz$ which is within the coherence bandwidth. Assuming that available $BW = 1.5MHz$. The number of subcarriers is: $N = \frac{BW}{f_\Delta} = \frac{1.5MHz}{10KHz} = 150$. For the sake of design simplicity , the FFT size is selected as: $N = 128$. Using 4 subcarriers as virtual carriers on both sides to ease the filtering process, we are left with useful subcarriers $N_u = 120$ for data transmission.

Using QPSK as baseband modulation and modulation constant $M = 2\ bits\ per\ symbol$, we get the raw data transfer rate:

$$R_{b=}\frac{N_u\ M}{(T + T_G)} = \frac{(100)(2bits\ per\ symbol)}{108\mu sec} = 2.22Mbps$$

Achievable data rate of $2.22Mbps$ is well above the required data rate and will take care of overhead in form of CP.

BIBLIOGRAPHY

[1] G. J. Foschini, "On limits of wireless communications in a fading environment when using multiple antennas," *Wireless Personal Communications,* vol. 6, no. 3, pp. pp. 311-35, Mar. 1998.

[2] I. Koffman and V. Roman, "Broadband Wireless Acess Solutions on OFDM Access in IEEE 802.16," *IEEE Commun. Mag.,* vol. 40, no. 4, p. 96–103, April 2002.

[3] Y. Li and G. Stüber, Orthogonal Frequency Division Multiplexing for Wireless Communications, Boston, MA: Springer-Verlag, 2006.

[4] J. A. C. Bingham, "Multicarrier modulation for data transmission: An idea whose time has come," *IEEE Commun. Mag.,* vol. 28, no. 5, p. 5–14, May 1990.

[5] A. R. S. Bahai and B. R. Saltzberg, Multi-Carrier Digital Communications: Theory and Applications of OFDM, New York: Plenum, 1999.

[6] A. N. Mody and G. L. Stuber, "Receiver Implementation for a MIMO OFDM System," *Global Communications Conference, Globecom,* vol. 1, pp. 716-720, 2002.

[7] E. Biglieri, R. Calderbank, A. Constantinides, A. Goldsmith, A. Paulraj and V. H. Poor, MIMO Wireless Communications, Cambridge, U.K: Cambridge Univ. Press, 2007.

[8] H. Yang, "A road to future broadband wireless access: MIMO-OFDM based air interface," *IEEE Commun. Mag.,* vol. 43, no. 1, p. 53–60, Jan. 2005.

[9] H. Bölcskei, "MIMO-OFDM wireless systems: Basics, perspectives, and challenges," *IEEE*

Wireless Commun., vol. 13, no. 4, pp. 31-37, Aug. 2006.

[10] G. L. Stuber, J. R. Barry, S. W. McLaughlin, Y. Li, M. A. Ingram and a. T. G. Pratt, "Broadband MIMO-OFDM wireless communications," *Proc. IEEE,* vol. 92, no. 2, p. 271–294, Feb. 2004.

[11] A. Sendonaris, E. Erkip and B. Aazhang, "User cooperation diversity—Part I: System description," *IEEE Trans. Commun.,* vol. 51, no. 11, p. 1927–1938, Nov. 2003.

[12] X. Li, "Space-time coded multi-transmission among distributed transmitters without perfect synchronization," *IEEE Signal Process. Lett.,* vol. 11, no. 12, p. 948–951, Dec. 2004.

[13] P. Mitran, H. Ochiai and V. Tarokh, "Space-time diversity enhancements using space-time collaboration," *IEEE Trans. Inf. Theory,* vol. 51, no. 6, p. 2041–2057, Jun. 2005.

[14] A. Nosratinia, T. E. Hunter and A. Hedayat, "Cooperative communication in wireless networks," *IEEE Commun. Mag,* vol. 42, no. 10, p. pp. 74–80, Oct. 2004.

[15] IEEE, "Part 16: Air Interface for Broadband Wireless Access Systems, Ammendment 1: Multihop Relay specification," IEEE LAN/MAN standard 802.16j, 2009.

[16] M. I. Cheema and S. A. Khan, "A Robust Coarse Timing Synchronizer Design for Cooperative Diversity OFDM System," *International Journal of Information and Electrical Engineering (IJIEE),* vol. 03, no. 06, Nov. 2013.

[17] M. I. Cheema and S. A. Khan, "A Simple Carrier Frequency Offset Synchronization strategy for Multiple Relay Cooperative Diversity OFDM System," *Pakistan Journal of Engineering and Applied sciences (PJEAS),* vol. Accepted for publication, 2013.

[18] M. I. Cheema and S. A. Khan, "A Low Complexity Fine Timing Offset and Channel Estimation Algorithm for Cooperative Diversity OFDM System," in *The IEEE International Conference on Communications and Information Technology(ICCIT)*, Aqaba, Jordan, 2011.

[19] S. Weinstein and P. Ebert, "Data transmission by frequency-division multiplexing using the discrete fourier transform," *IEEE Trans. on Commun.,* vol. 19, no. 5, pp. 628-634, October 1971.

[20] M. Speth, S. A. Fechtel, G. Fock and M. H., "Optimum receiver design for wireless broad-band systems using OFDM—Part I," *Communications, IEEE Transactions on,* vol. 47, no. 11, p. 1668–1677, Nov. 1999.

[21] M. Speth, D. Daecke and H. Meyr, "Minimum overhead burst synchronization for OFDM based broadband transmission," *Proc. Global Telecommun. Conf.,* p. 2777–2782, November 1998.

[22] D. L. Goeckel and Y. Hao, "Space-time coding for distributed antenna arrays," *Proc. IEEE Int. Conf. Commun.,* p. 747–751, Jun. 2004.

[23] O.-S. Shin and V. Tarokh, "Design of an OFDM Cooperative Space-Time Diversity System," *IEEE Transactions on Vehicular Technology,* vol. 56, no. 4, pp. 2203-2215, July 2007.

[24] W. D. Warner and C. Leung, "OFDM/FM frame synchronization for mobile radio data communication," *IEEE Trans. on Vehicular Technology,* vol. 42, no. 3, pp. 302-313, 1993.

[25] H. Nogami and Nagashimi, "A frequency frequency and timing period acquisition

technique for OFDM systems and timing period acquisition technique for OFDM systems," *Proc. Personal, Indoor and Mobile Radio Communications (PIMRC),* vol. 3, p. 1010–1015, September 1995.

[26] T. M. Schmidl and D. C. Cox, "Robust frequency and timing synchronization for OFDM," *IEEE Trans. Commun.,* vol. 25, no. 12, p. 1613–1621, December 1997.

[27] K. Shi and E. Serpedin, "Coarse frame and carrier synchronization of OFDM systems: A new metric and comparison," *IEEE Trans. Wireless Commun.,* vol. 3, no. 4, p. 1271–1284, July 2004.

[28] H. Minn, V. K. Bhargava and K. B. Letaief, "A robust timing and frequency synchronization for OFDM systems," *IEEE Trans. Wireless Commun.,* vol. 2, no. 4, p. 822–839, uly 2003.

[29] H. Minn, M. Zeng and V. K. Bhargava, "On timing offset estimation for OFDM system," *IEEE Commun. Lett.,* vol. 4, p. 242–244, July 2000.

[30] J. J. v. d. Beek, P. O. Bo¨rjesson, M. L. Boucheret, D. Landstro¨m, J. M. Arenas, O. O¨dling, C. O¨stberg, M. Wahlqvist and S. K. Wilson, "A time and frequency synchronization scheme for multiuser OFDM," *IEEE J. Select. Areas Commun.,* vol. 17, no. 11, p. 1900–1914, Nov. 1999.

[31] B. Yang, K. B. Letaief, R. S. Cheng. and Z. Cao, "Timing recovery for OFDM transmission," *IEEE J. Select. Areas Commun.,* vol. 18, p. 2278–2290, Nov. 2000.

[32] A. J. Coulson, "Maximum likelihood synchronization for OFDM using a pilot: Algorithms," *IEEE J. Sel. Areas Commun.,* vol. 19, no. 12, p. 2486–2494, December 2001.

[33] O.-S. Shin, H. T. Kung and V. Tarokh, "Construction of block orthogonal Golay sequences and application to channel estimation of MIMO-OFDM systems," *IEEE Trans. Commun.,* May 2007.

[34] T. M. Schmidl and D. C. Cox, "Robust frequency and timing synchronization for OFDM," *IEEE Trans. Commun,* vol. 45, no. 12, p. 1613–1621, Dec. 1997.

[35] M. Morelli, J. Kuo and M. O. Pun, "Synchronization techniques for orthogonal frequency division multiple access (OFDMA): A tutorial review," *Proc. IEEE,* vol. 19, no. 7, p. 1394–1427, July 2007.

[36] P. H. Moose, "A technique for orthogonal frequency division multiplexing frequency offset correction," *IEEE Trans. Commun,* vol. 42, no. 10, p. 2908–2914, Oct. 1994.

[37] F. Classen and H. Meyr, "Frequency synchronization algorithms for OFDM systems suitable for communication over frequency selective fading channels," in Proceedings of IEEE the Global Telecommunications Conference," *IEEE the Global Telecommunications Conference,* vol. 3, pp. 1655-1659, 1994.

[38] H. Sari, G. Karam and I. Jeanclaude, "Transmission techniques for digital terrestrial tv broadcasting," *IEEE Communications Magazine,* pp. 100-109, January 1995.

[39] M. Morelli and U. Mengali, "An improved frequency offset estimator for OFDM applications," *IEEE Commun. Lett.,* vol. 3, no. 3, p. pp. 75–77, Mar. 1999.

[40] S. Barbarossa, M. Pompili and G. B. Giannakis, "Channel-independent synchronization of orthogonal frequency division multiple access systems," *IEEE J. Select. Areas Commun.,* vol. 20, no. 2, p. 474–486, Feb. 2002.

[41] R. O. Schmidt, "Multiple emitter location and signal parameter estimation," vol. 34, p. 243–258, Mar. 1986.

[42] Z. Cao, U. Tureli and Y. D. Yao, "Deterministic multiuser carrier-frequency offset estimation for interleaved OFDMA uplink," *IEEE Trans. Commun.,* vol. 52, no. 9, p. 1585–1594, Sep. 2004.

[43] M. Morelli, "Timing and frequency synchronization for the uplink of an OFDMA system," *IEEE Trans. Commun.,* vol. 52, no. 2, p. 296–306, Feb. 2004.

[44] J. A. Fessler and A. O. Hero, "Space-alternating generalized expectation-maximization algorithm," *IEEE Trans. Signal Process.,* vol. 42, no. 10, p. 2664–2677, Oct. 1994.

[45] M. O. Pun, M. Morelli and C. C. J. Kuo, "Iterative detection and frequency synchronization for OFDMA uplink transmissions," *IEEE Trans. Wireless Commun.,* vol. 6, no. 2, p. 629–639, Feb. 2007.

[46] M. O. Pun, M. Morelli and C. J. Kuo, "Maximum-likelihood synchronization and channel estimation for OFDMA uplink transmissions," *IEEE Transactions on Communications,* vol. 54, no. 4, p. 726–736, April 2006.

[47] Q. Huang, M. Ghogho and J. Wei, "Data detection in cooperative STBC OFDM systems with multiple frequency offsets," *IEEE Signal Processing Letters,* vol. 16, no. 7, pp. 600-603, 2009.

[48] J. Choi, C. Lee, H. W. Jung and Y. H. Lee, "Carrier frequency offset compensation for uplink of OFDM-FDMA systems," *IEEE Communications Letters,* vol. 4, no. 12, p. 414–416, December 2000.

[49] D. Huang and K. B. Letaief, "An interference cancellation scheme for carrier frequency offsets correction in OFDMA systems," *IEEE Transactions on Communications,* vol. 53, no. 7, p. 1155–1165, July 2005.

[50] X. Li, F. Ng and T. Han, "Carrier frequency offset mitigation in asynchronous cooperative OFDM transmissions," *IEEE Transactions on Signal Processing,* vol. 56, no. 2, pp. 675-685, 2008.

[51] Q. Huang, M. Ghogho, J. W. a and P. Ciblat, "Practical timing and frequency synchronization for OFDM based Cooperative systems," *IEEE Trans. on Signal Processing,* vol. 58, no. 7, p. 3706–3716, July 2010.

[52] P. Murphy and A. Sabharwa, "Design, Implementation, and Characterization of a Cooperative Communications System," *IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY,* vol. 60, no. 6, July 2011.

[53] H. Minn and V. K. Bhargava, "An investigation into time-domain approach for OFDM channel estimation," *IEEE Trans. Broadcast.,* vol. 46, pp. 240-248, Dec. 2000.

[54] X. Wang, Y. Wu, J.-Y. Chouinard, S. Lu and B. Caron, "A channel characterization technique using frequency domain pilot time domain correlation method for DVB-T systems," *IEEE Trans. on Consumer Electronics,* vol. 49, no. 4, p. 949–957, Nov. 2003.

[55] D. Huang and K. B. Letaief, "An interferencecancellation scheme for carrier frequency offsets correction in OFDMA systems," *IEEE Transactions on Communications,* vol. 53, no. 7, p. 1155–1165, July 2005.

[56] U. Lambrette, M. Speth and H. Meyr, "OFDM burst frequency synchronization by single

carrier training data," *IEEE Commun. Lett,* vol. 1, no. 2, p. 46–48, Mar. 1997.

[57] A. Czylwink, "Synchronization for systems with antenna diversity," *IEEE Veh. Technol. Conf.,* vol. 2, no. 50, p. 728–732, Sep. 1999.

[58] B. Park, "A novel timing estimation method for OFDM systems," *IEEE Commun. Lett.,* vol. 7, no. 5, p. 239–241, May 2003.

[59] V. Erceg, K. Hari, M. Smith and D. Baum, "Channel Models for Fixed Wireless Applications," *Contribution IEEE 802.16.3c-01/29r1,* Febraury 2001.

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