FREQUENCY SYNCHRONIZATION IN MULTIUSER OFDM-IDMA SYSTEMS

By

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University of KwaZulu-Natal, Durban, South Africa

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TITLE

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Submitted in completion of the academic requirements for the degree of M.Sc. Engineering

School of Engineering, Discipline of Electrical, Electronic and Computer Engineering

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October 2013

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Date: ______________________________

DECLARATION

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DEDICATION

To the only wise God -The Alpha and the Omega

"How precious also are thy thoughts unto me, O God! How great is the sum of them!" –Psalms 139:17

PREFACE

The research work in this thesis was implemented by Muyiwa Balogun, under the supervision of Professor S.H. Mneney and co-supervised by Dr. O.O. Oyerinde at the Discipline of Electrical, Electronic and Computer Engineering, University of KwaZulu-Natal, Howard College, Durban. This research work was supported by Telkom South Africa, through the Center for Radio Access and Rural Technology (CRART).

Parts of this thesis have been presented at the IEEE International Conference on Wireless Communication Society, Vehicular Technology, Information Theory, and Aerospace & Electronics Systems Technology (Global Wireless Summit '13) in Atlantic City, USA; SATNAC 2013 conference held at the Spier wine Estate, Stellenbosch; and the IEEE AFRICON Conference 2013 in Mauritius. Parts of this thesis are also under review for publication by the South African Institute of Electrical Engineers (SAIEE) research journal and the international Journal of Cyber Security and Mobility.

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ABSTRACT

Various multiuser schemes have been proposed to efficiently utilize the available bandwidth while ensuring an acceptable service delivery and flexibility. The multicarrier CDMA became an attractive solution to the major challenges confronting the wireless communication system. However, the scheme is plagued with multiple access interference (MAI), which causes conspicuous performance deterioration at the receiver. A low-complexity multiuser scheme called the Interleave Division Multiple Access (IDMA) was proposed recently as a capable solution to the drawback in the multicarrier CDMA scheme. A combined scheme of OFDM-IDMA was later introduced to enhance the performance of the earlier proposed IDMA scheme. The multicarrier IDMA scheme therefore combats inter-symbol interference (ISI) and MAI effectively over multipath with low complexity while ensuring a better cellular performance, high diversity order, and spectral efficiency.

Major studies on the OFDM-IDMA scheme emphasis only on the implementation of the scheme in a perfect scenario, where there are no synchronization errors in the system. Like other multicarrier schemes, the OFDM-IDMA scheme however suffers from carrier frequency offset (CFO) errors, which is inherent in the OFDM technique. This research work therefore examines, and analyzes the effect of synchronization errors on the performance of the new OFDM-based hybrid scheme called the OFDM-IDMA. The design of the OFDM-IDMA system developed is such that the cyclic prefix duration of the OFDM component is longer than the maximum channel delay spread of the multipath channel model used. This effectively eliminates ISI as well as timing offsets in the system. Since much work has not been done hitherto to address the deteriorating effect of synchronization errors on the OFDM-IDMA system, this research work therefore focuses on the more challenging issue of carrier frequency synchronization at the uplink.

A linear MMSE-based synchronization algorithm is proposed and implemented. The proposed algorithm is a non-data aided method that focuses on the mitigation of the ICI induced by the residual CFOs due to concurrent users in the multicarrier system. However, to obtain a better and improved system performance, the Kernel Least Mean Square (KLMS) algorithm and the normalized KLMS are proposed, implemented, and effectively adapted to combat the degrading influence of carrier frequency offset errors on the OFDM-IDMA scheme. The KLMS

synchronization algorithm, which involves the execution of the conventional Least Mean Square (LMS) algorithm in the kernel space, utilizes the modulated input signal in the implementation of the kernel function, thereby enhancing the efficacy of the algorithm and the overall output of the multicarrier system.

The algorithms are applied in a Rayleigh fading multipath channel with varying mobile speed to verify their effectiveness and to clearly demonstrate their influence on the performance of the system in a practical scenario. Also, the implemented algorithms are compared to ascertain which of these algorithms offers a better and more efficient system performance. Computer simulations of the bit error performance of the algorithms are presented to verify their respective influence on the overall output of the multicarrier system. Simulation results of the algorithms in both slow fading and fast fading multipath scenarios are documented as well.

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LIST OF ABBREVIATIONS

1G	First Generation Network
2G	Second Generation Network
3G	Third Generation Network
3GPP	Third Generation Partnership Project
4G	Fourth Generation Network
ADC	Analog-to-Digital Converter
AMPS	Advanced Mobile Phone Systems
APP	*a Posteriori Probability*
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
CDMA	Code Division Multiple Access
CFO	Carrier Frequency Offset
CP	Cyclic Prefix
DAB	Digital Audio Broadcasting
DAC	Digital-to-Analog Converter
DDCE	Decision Directed Channel Estimation
DEC	Decoders
DFT	Discrete Fourier Transform
DVB	Digital Video Broadcasting
ESE	Elementary Signal Estimator
FDM	Frequency Division Multiplexing
FDMA	Frequency Division Multiple Access
FEC	Forward Error Correction

FFT	Fast Fourier Transform
GSM	Global System for Mobile Communication
HPA	High Power Amplifier
ICI	Inter Channel Interference
IDFT	Inverse Discrete Fourier Transform
IDMA	Interleave Division Multiple Access
IFFT	Inverse Fast Fourier Transform
IMT	International Mobile Telecommunications
ISI	Inter Symbol Interference
ITU	International Telecommunication Union
KLMS	Kernel Least Mean Square
LAN	Local Area Network
LLR	Logarithm Likelihood Ratio
LMS	Least Mean Square
LO	Local Oscillator
LOS	Line of Sight
LTE	Long Term Evolution
MAI	Multiple Access Interference
MAN	Metropolitan Area Network
MC	Multicarrier
MMSE	Minimum Mean-Squared Error
MUD	Multiuser Detection
NKLMS	Normalized Kernel Least Mean Square
OFDM	Orthogonal Frequency Division Multiplexing
PAPR	Peak-to-Average Power Ratio

PDC	Personal Digital Cellular
QOS	Quality of Service
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
TDMA	Time Division Multiple Access
VLSI	Very Large Scale Integration

LIST OF NOTATIONS

B_C	Channel bandwidth
D_s	Spread spectrum bandwidth
f_c	Carrier frequency
λ	Signal wavelength
P_R	Received signal power
v	Mobile velocity
d	Distance
l	Propagation length
$\Delta\delta$	Phase angle
f_d	Doppler shift
P_T	Transmitted signal power
S_{Tt}	Total available spectrum
C_b	Coherence bandwidth
D_θ	Channel delay spread
Ng	Guard interval
β	Peak-to-Average Power Ratio
$x(t)$	Transmitted signal
$h_k(n)$	Fading channel coefficient
$d(n)$	Additive White Gaussian Noise
ב$_k(n)$	Multiuser interference
$r(n)$	Received signal
N	Number of sub-carriers
ε_k	Carrier Frequency Offset
Q_s	Data symbol energy

N_0	Power spectral density
n	sub-carrier index
$J_c(m)$	MMSE cost function
ᶒ(m)	Update error signal
μ	KLMS step-size
Ӄ	Kernel function
γ	Kernel width parameter

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

Wireless communication has recorded a phenomenal and exponential growth especially in recent decades. After some initial as well as important breakthrough in radio wave research at the twilight of the nineteenth century, wireless communication and its applications have become an integral part of the modern world. Although there are many applications of the wireless communication, the mobile cellular systems have enjoyed the most popularity and unprecedented growth. Mobile communication systems as shown in Fig. 1-1 have however experienced some metamorphoses over the years with the aim of providing consumers with reliable and improved services. The earlier mobile communication systems, usually referred to as 1G systems [1], were analog based. A decade before the end of the twentieth century, the 2G mobile communication systems were introduced, based on digital communication technology, and expectedly offered better services [2]. The 2G systems, rolled out on the GSM standard, support both wireless transmissions of voice as well as data services unlike the earlier generations that only provide voice transmission. An improvement on the typical 2G system, which could only offer slow data transmission, is the 2.5G cellular system [3]. The 2.5G systems offer expanded services such as short messages, multimedia messages, and basic internet access with improved speed and quality. These generations of communication systems still have great popularity especially in the developing countries.

The mobile communication market continues to enjoy overwhelming growth and popularity such that developers have to keep pace with growing demands and services. The 3G systems were launched as a solution to high data-rate transmission and users' demand for multiuser services. The 3G networks are based on the International Mobile Telecommunications-2000 (IMT-2000) standards, supporting data transmission of up to 2Mbits/s. Three major multiple access schemes, namely; FDMA, TDMA and CDMA are supported by the IMT-2000 standard, allowing about five radio interface which account for the high flexibility of the 3G communication systems [3].

The need for an improved performance and cellular capacity informed the introduction of the 3G-LTE systems, meant to serve as a temporal solution before the full roll out of the 4G systems. The features and specifications of the 4G systems have been comprehensively stated and approved by the ITU [4], to ensure that efficient architecture as well as state-of-art technologies, which offer high data-rate transmission, reliability, and system flexibility, are adopted. Various multiple access schemes have been considered for the 4G communication systems with special focus on spectral efficiency and system complexity. OFDM-based multiple access schemes and associated hybrid technologies have become popular and have been the focus of recent mobile communications research because of their inherent advantages which include efficient and reliable high data-rate transmission as well as low system complexity.

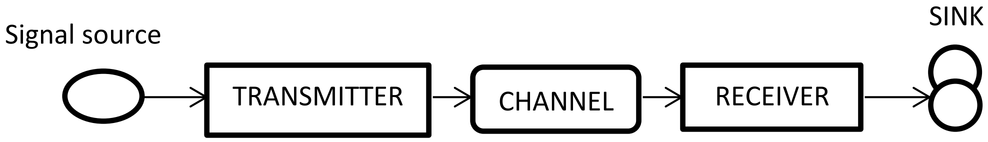

Fig. 1-1 Simple block diagram of a Communication System

1.1. Multiple Access Scheme

The allocation of channels to different users in such a way that the limited spectrum is well utilized is vital in wireless communications design. The idea of Multiple Access comes in when dedicated channels are assigned to different users in a communication system. To achieve this, various techniques have been used by previous generations of cellular systems. However, the popular techniques involve sharing the available bandwidth based on time slot, frequency, or codes, as the case may be, to multiple users. Thus, the major techniques, as employed in the different generations of cellular communications are discussed below.

1.1.1. Frequency Division Multiple Access

Frequency Division Multiple Access (FDMA) involves the assignment of different frequency channels to different users in the cellular system. Users in the system share the available bandwidth based on frequency allocation and they do not share the same channel during transmission. Guard bands are introduced between channels as a measure against interference and multipath delay spread. Frequency-selective fading is not a challenge as the divided channels are usually narrowband. Transmission in FDMA is continuous and frequency sensitive radios are needed which can tune to different channels at the receiver. Each user in the system is assigned paired frequencies that are used during uplink and downlink processes. FDMA is considered wasteful since a particular channel lies idle if the assigned user is not active, as other users cannot access the channel. However, FDMA was the most widely used scheme for analog communication systems. It was the scheme utilized by the first US analog cellular system called the Advanced Mobile Phone systems (AMPS). The total number of users that can be supported concurrently over the available bandwidth in the FDMA scheme can be represented mathematically as [5, 6]

$$N = \frac{S_{Tt} - 2B_{GB}}{B_C}, \tag{1.1}$$

where S_{Tt} is the total available spectrum, B_{GB} is the guard band for multipath delays and interference while B_C is the channel bandwidth.

1.1.2. Time Division Multiple Access

In Time Division Multiple Access (TDMA), users have access to the whole of the available bandwidth but are limited in time, as radio transmission for any particular user in the system is discontinuous. Users are assigned distinct time slots during which they can either transmit or receive radio signals. Assignment of multiple channels to one user is possible in TDMA, which is easily accomplished by assigning multiple time slots to the user. Adequate provision must be made for an effective synchronization, as TDMA systems transmit in a burst manner. Receivers in the system therefore need to be synchronized for each signal burst, which invariably increases the overhead of the system. Guard bands are introduced into the cellular system as a measure against Adjacent Channel Interference. Two guards are usually employed for this purpose, one utilized as a prefix at one end of the allotted frequency and the other as a postfix at the other end. TDMA is the technology employed in the GSM technology as well as in the Personal Digital Cellular (PDC) standards [5]. The total number of concurrent user channels available in a TDMA system can be expressed mathematically as [6]

$$N = \frac{n(S_{Tt} - 2B_{GB})}{B_C}, \tag{1.2}$$

where n is the maximum number of users supported per radio channel, while B_C is the channel bandwidth.

1.1.3. Code Division Multiple Access

The spread spectrum Code Division Multiple Access (CDMA) was earlier used predominantly in military cellular transmission [7]. The CDMA scheme essentially involves the assignment of spreading codes, which are mutually orthogonal, to users in the system. Input signals are transmitted over bandwidth that is way larger than the required bandwidth for transmission. The spreading operation carried out in CDMA makes it robust against multipath fading and improves the process gain of the communication system. At the receiver, the process gain is expressed as the ratio of the spread spectrum bandwidth D_s to the actual bandwidth of the transmitted radio signal D_o . This can be written as

$$P_{gain} = \frac{D_s}{D_o}. \tag{1.3}$$

Due to the loss of orthogonality among the spreading sequence of simultaneous users, multiple access interference results in CDMA, which causes degradation in the cellular system. The use of multiuser detection has rather increased system complexity and this is still a major challenge in CDMA systems. However, the CDMA scheme, known for its high flexibility, multipath tolerance, and reliable data encryption, is the technology that has been widely used in the 3G and 3G-LTE cellular networks [3, 6].

1.2. Peculiarity of the Wireless Channel

Wireless communication, which essentially involves the transmission of data over radio channel, is often faced with technical issues and challenges due to the unreliable nature of the transmission channel. The transmissions through air or radio channel are typically confronted with different types of interference, including the ones that result from the cellular arrangement pattern as shown in Fig. 1-2, as well as various levels of fading before getting to the intended destination. It is therefore important to consider the major features and challenges confronting the wireless communication technology, which are fundamental to the design and implementation of any cellular communication scheme.

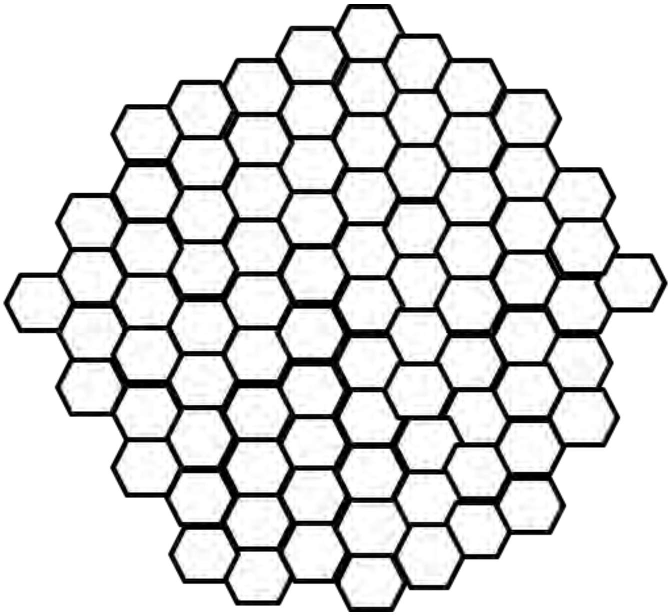

Fig. 1-2 Hexagonal arrangement of cells in a cellular system

1.2.1. Path Loss

Assuming there are no obstructions between the sender and the receiver, radio signals are normally propagated as light waves in free space following a straight line, usually referred to as line-of-sight (LOS). Attenuation of radio signals occur due to the distance of separation between the transmitter and the receiver [8]. Path loss therefore defines the average radio signal attenuation in free space, being a function of the physical distance between the transmitter and the receiver. The resulting radio signal reaching the receiver is given as [5]

$$s(t) = Re\left[\frac{\lambda\sqrt{A_l}e^{-j2\pi d/\lambda}}{4\pi d} m(t)e^{j2\pi f_c t}\right], \tag{1.4}$$

where $\sqrt{A_l}$ denotes the transceiver antenna wave pattern following the LOS path, f_c is the carrier frequency, λ represents the signal wavelength, $m(t)$ is the complex envelope of the transmitted signal and $e^{-j2\pi d/\lambda}$ is the phase shift due to the distance d travelled by the radio wave. Therefore, path loss, which is the ratio of the received signal power to the power of the transmitted signal P_T, can be expressed from equation (1) as [5]

$$\frac{P_R}{P_T} = \left[\frac{\sqrt{A_l}\lambda}{4\pi d}\right]^2. \tag{1.5}$$

The above expression shows that the received signal power P_R diminishes in proportion to the square inverse of the distance between the transmitter and the receiver of a communication system.

1.2.2. Shadowing

Path loss as described above becomes greatly significant when propagation is over a long distance and when radio signals experience reflections and obstructions along the paths of propagation [8]. This is the actual scenario encountered practically in mobile communication, so that the attenuation experienced by the transmitted signal becomes dependent on the nature and characteristics of the environment. Thus, the fluctuations experienced by radio signals due to obstructions such as buildings, hills, etc. as illustrated in Fig. 1-3, along the paths of propagation is referred to as Shadowing [9]. The consideration of the signal energy loss due to shadowing is therefore vital for effective transceiver design and in the prediction of cellular coverage and quality of service (QoS).

1.2.3. Doppler Shift

The received frequency often experiences variations due to the relative movement of the transmitter. The change in the frequency due to the relative movement between the transmitter and the receiver of a communication system is termed Doppler shift. Doppler shift, as shown in Fig. 1-4, can be described by considering a mobile system moving at a velocity v with relative difference in propagation length given as $l = dcos\delta$, where the distance $d = v\Delta t$. The phase angle is written as [10]

$$\Delta\delta = {}^{2\pi l}/_{\lambda} = \frac{2\pi dcos\delta}{\lambda}, \tag{1.6}$$

and therefore the Doppler shift in the cellular system can be expressed as

$$f_d = \left({}^{1}/_{2\pi}\right) * \left({}^{\Delta\delta}/_{\Delta t}\right) = \frac{v}{l}cos\delta. \tag{1.7}$$

Movements can be either towards or away from the signal source. Doppler frequency shift has a negative value when the sender moves away from the receiver and vice versa. Doppler shift comes as frequency offset which changes with mobile speed and direction. It is therefore pertinent to ensure during cellular design that the system is capable of tracking adequately, the quick change in frequency offset and variation as the mobile velocity changes [10, 11].

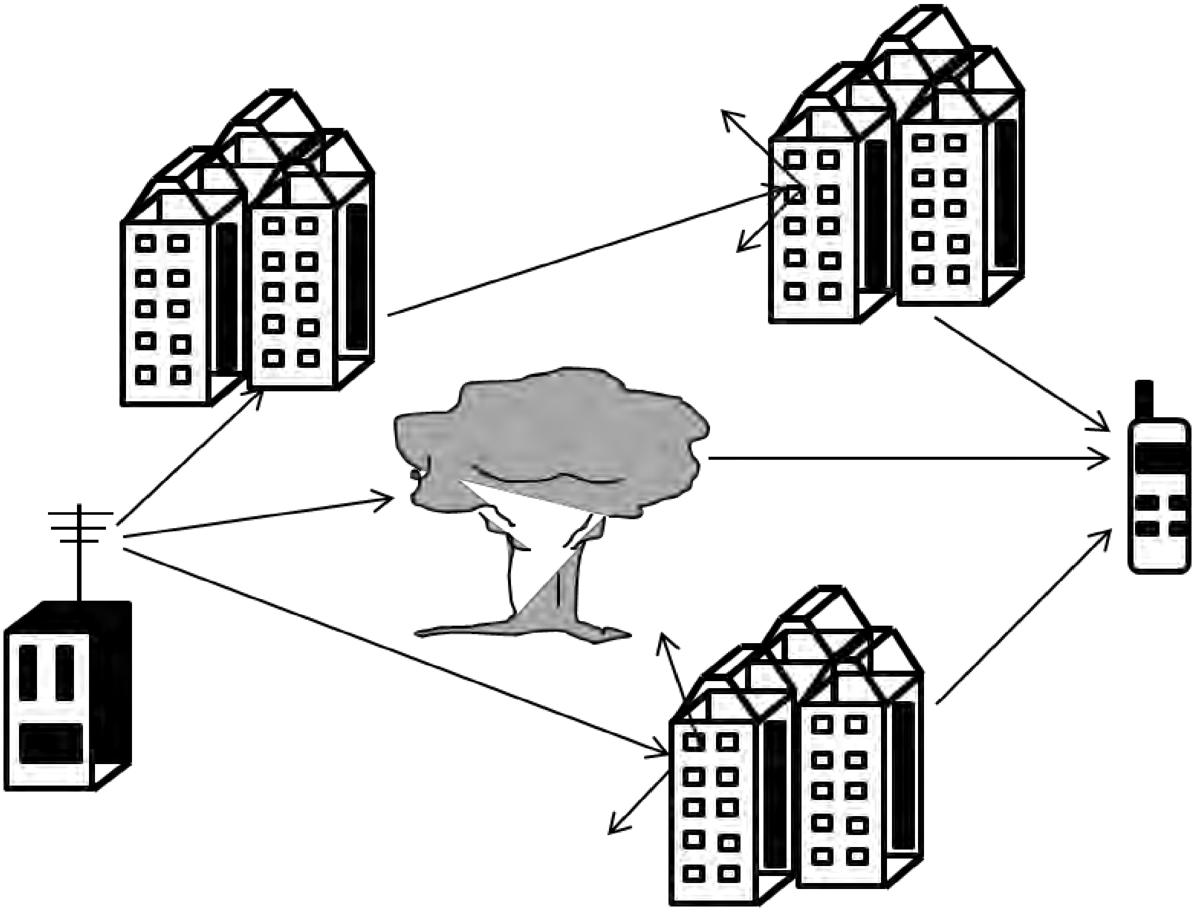

Fig. 1-3 Multipath illustration between the transmitter and the receiver

1.2.4. Delay Spread

As mentioned earlier, radio signals experience various degrees of attenuations through reflections and obstructions along the path of propagation. Consequently, transmitted signals arrive at the receiver end of the communication system through multiple paths at different times with varying signal power. Delay spread is therefore the difference in the propagation time between the longest and the shortest propagation path taken by radio signals in a cellular system while considering only the paths of signals with substantive energy [12]. Delay spread is an occurrence of great significance in mobile communication as it causes inter-symbol interference (ISI), which results from the overlapping of the symbols of delayed radio signals with the subsequent symbols. This causes an increase in the bit error rate and degradation in cellular performance. Thus, there must be adequate provision during design to address the delay spread, which is also a factor that determines the frequency coherence of a cellular system.

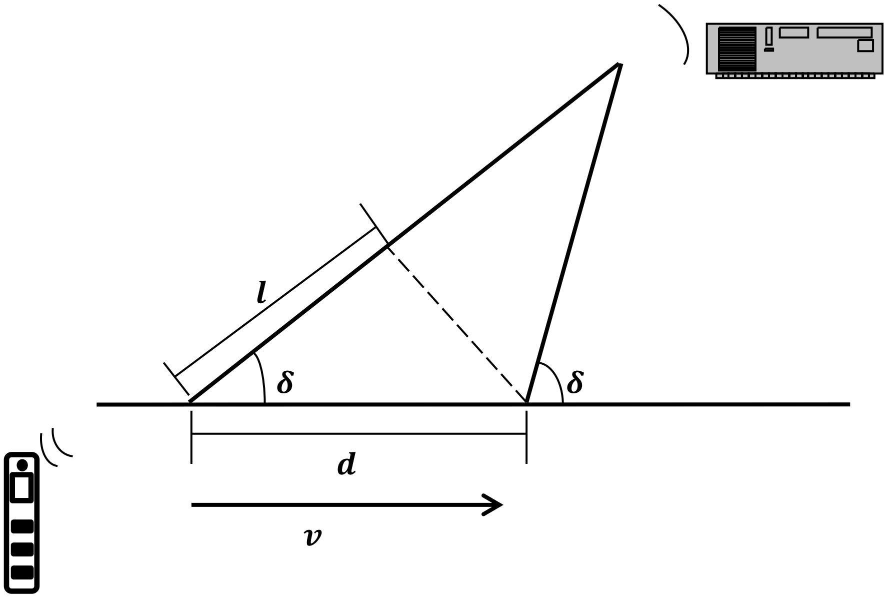

Fig. 1-4 Doppler Effect in mobile communication

1.2.5. Coherence Bandwidth

The coherence bandwidth of a communication channel is largely dependent on the delay spread discussed earlier. It is a statistical measure of the channel frequency response and is proportional to the inverse of the delay spread. Coherence bandwidth C_b can therefore be expressed as [12]

$$C_b = \frac{1}{2D_\theta}, \tag{1.8}$$

where D_θ represents the channel delay spread.

Coherence bandwidth determines the flatness or the frequency-selective characteristics of a communication channel. It describes the range of frequency across which two frequency components of the radio channel become correlated in amplitude [6]. During transmission, if the bandwidth of the radio signal is significantly less than the coherence bandwidth C_b, with bandwidth $B \ll C_b$, the channel is seen as Flat-fading. The radio signal bandwidth is said to be effectively correlated in amplitude as almost equal fading is experienced over the entire channel bandwidth. Flat-fading channels, described as amplitude varying channels cause fluctuations in channel gain, resulting in deep fades, which may require an increase in transmitter power up to 30dB. Through effective coding and diversity techniques, this challenge can be adequately addressed in cellular systems [5].

At the instance when the radio signal bandwidth is significantly greater than the coherence bandwidth, there is wide variation in the channel amplitude over the entire bandwidth. The channel is said to be Frequency-selective with bandwidth $B \gg C_b$. Frequency-selective fading channels are also referred to as wideband channels because the bandwidth of the transmitted radio signal is ‘wider’ than the bandwidth of the impulse response of the radio channel [5, 10]. Frequency-selective fading, which is mainly due to the time variation of transmitted symbols caused by multipath delays, poses a greater challenge than frequency nonselective or flat-fading channels, causing inter-symbol interference (ISI) within the radio channel [11, 12] . This challenge can be adequately addressed by the use of effective multicarrier schemes such as OFDM-based techniques.

1.2.6. Fast Fading and Slow Fading

Radio channels can be considered as either slow fading or fast fading, depending on how quickly the baseband radio signal varies in relation to the change rate of the radio channel. A channel is considered as slow fading when the rate at which the channel impulse response varies is significantly slower than the baseband radio signal. The implication of this is that the bandwidth of the baseband radio signal B is much higher than the Doppler spread D_B of the radio channel in the frequency domain. Hence, a signal experiences slow fading when $B \gg D_B$.

In the case where the impulse response of the radio channel changes at a quicker rate within the symbol period, the channel is said to be experiencing fast fading. This results in frequency dispersion, which in turn causes alteration in the transmitted radio signal. This undesirable distortion in the transmitted signal increases as the Doppler spread increases in relation to the bandwidth of the radio signal. Thus, a signal experiences fast fading when $B \ll D_B$. It is however important to note that the speed of the mobile unit and the baseband radio signaling decides if a signal experiences slow fading or fast fasting [6, 11].

1.3. Motivation and Research Objective

The unprecedented growth and demand for wireless communication services has been overwhelming especially in recent decades. There has been a surge, more than ever before in the number of subscribers, desiring improved and reliable communication services even in the face of a limited spectrum. Also, wireless communication comes with its own peculiarity and challenges, which must be addressed in order to provide good quality of service to users. Effective mobile communication schemes are therefore needed to be put in place to ensure the continuous provision of reliable services while ensuring an efficient management of the scarce spectrum.

Various multicarrier schemes have been used in the past to enable multiple users access the available spectrum simultaneously. However, the need for better quality of service, improved capacity and high data-rate transmission, which has become nonnegotiable, has informed the continuous search for a reliable and efficient multicarrier scheme. The Code Division Multiple Access (CDMA) and the Orthogonal Frequency Division Multiplexing (OFDM) techniques rank high above other multiuser schemes due to their inherent advantages. The OFDM technique has particularly become difficult to ignore and almost indispensible because of its support for high data rate transmission and the ability to suppress ISI without much difficulty. Thus, OFDM has now become the bedrock of most recent multicarrier schemes in wireless communication.

The combination of the CDMA and the OFDM technique to form a hybrid scheme of OFDM-CDMA has gained prominence and considered attractive due to the diversity and radio resource management flexibility offered. As studied in [13, 14], there are various methods of combining the OFDM and the CDMA scheme, but the main idea behind the multicarrier CDMA hybrid scheme is to perform a spreading operation on transmitted signals which are then converted into parallel streams. The serial-to-parallel converted data are then modulated over different subcarriers, which are mutually orthogonal, and transmitted over the radio channel. The spreading code assigned to each user is to enable signal separation at the receiver. However, due to diverse level of fading and attenuation experienced by the transmitted signals, orthogonality is lost among subcarriers. This leads to Multiple Access Interference (MAI), causing high degradation in cellular performance, which becomes severe as the number of simultaneous users increases.

In an effort to address the MAI in multicarrier CDMA (MC-CDMA), the Multiuser Detection (MUD) technique was introduced. The priority of the MUD is to subtract interfering signals from the input signal of each user in the system. However, the MUD technique utilized in MC-CDMA comes with associated complexities and high cost [15, 16]. Various MUD techniques have been proposed to address the high complexity of the MUD technique, but with little success. The complexity of the MUD tends to increase exponentially as the number of active subscribers increases. Recent studies have explored the possibility of the artificial neural network for multiuser detection [17] but these techniques tend to compromise system performance and efficiency for reduced complexity. The MUD challenge in MC-CDMA therefore remains and there has been a continuous search for an efficient and reliable scheme with low complexity.

To this end, a new multiuser scheme was recently proposed by *Li Ping* called the Interleave Division Multiple Access (IDMA) [18]. This scheme employs a simple low cost chip-by-chip iterative method for its multiuser detection. The IDMA scheme, which offers a lower system complexity compared to MC-CDMA [19], relies solely on interleaving as the only means of identifying signals from active users in the system. In a bid to achieve an improved cellular performance of the IDMA over multipath, *Mahafeno* in 2006 proposed an OFDM-based hybrid scheme called the OFDM-IDMA scheme [20]. The newly proposed multicarrier IDMA (MC-IDMA) scheme therefore combats ISI and MAI effectively over multipath with low complexity. The multicarrier scheme ensures a better cellular performance, high diversity order, and spectral efficiency compared to the MC-CDMA scheme. Thus, the scheme combines all the inherent advantages of the conventional IDMA and the OFDM technique. The associated MUD is of low cost and low complexity per user, which is independent of the number of simultaneous users in the system [21].

Major studies on the OFDM-IDMA scheme focus only on the implementation of the scheme in a perfect scenario, assuming that there are no synchronization errors in the system. This is not obtainable in practice. Recent studies however show that the OFDM component introduced makes the multicarrier system susceptible to synchronization errors, especially at the uplink. Synchronization errors, which results mainly from Doppler shifts and local oscillator instabilities [22], cause inter channel interference and loss of orthogonality among users. This subsequently leads to an overall reduced throughput and degraded cellular performance. Hence, the impact of synchronization errors on the recently proposed scheme must be addressed to obtain the best performance out of this noble scheme. This work therefore focuses thoroughly on the development and the implementation of synchronization algorithms, to combat the degrading impact of carrier frequency offset errors, thereby greatly improving the overall throughput of the multicarrier IDMA system.

1.4. Research Original Contribution

The contribution of this research work therefore is to examine, analyze, and verify the effect of synchronization errors on the performance of the recently proposed OFDM-based hybrid scheme called the OFDM-IDMA. The impact of synchronization errors on the multiuser scheme is also investigated in both slow fading and fast fading multipath channel. The design of the OFDM-IDMA system developed is such that the cyclic prefix duration of the OFDM component is longer than the maximum channel delay spread of the multipath channel model used. This effectively eliminates ISI as well as timing offsets in the system. Since much work has not been done hitherto to address the deteriorating effect of synchronization errors on the OFDM-IDMA system, this research work therefore focuses on the more challenging issue of carrier frequency synchronization at the uplink. A linear MMSE-based synchronization algorithm is proposed and implemented. Also, in order to achieve a better and improved system performance, another algorithm called the kernel Least Mean Square (KLMS) algorithm together with its normalized counterpart called the normalized KLMS is presented, implemented and effectively utilized to combat the effect of carrier frequency offset errors on the OFDM-IDMA scheme. The proposed algorithms have never been utilized to tackle synchronization errors in the OFDM-IDMA system to the best of our knowledge. Computer simulations are presented and the algorithms are further applied in a Rayleigh fading multipath channel with varying mobile speed to verify their effectiveness and to clearly demonstrate their influence on the performance of the system in a practical scenario. Also, the algorithms are comprehensively compared to ascertain which of the algorithms offers a better and more efficient system performance.

1.5. Thesis Organization

The layout of the rest of this thesis is as follows:

Chapter 2 gives a comprehensive review of the multicarrier IDMA scheme. The general principles of the IDMA scheme and the conventional OFDM technique are described and explained in details.

In Chapter 3, the multicarrier IDMA scheme is examined in the presence of Carrier Frequency offset (CFO) errors. The performance analysis of the OFDM-IDMA scheme in the presence of CFOs is carried out. Also, a linear MMSE-based synchronization algorithm is presented to combat the impact of CFOs in multicarrier IDMA. Computer simulations based on the bit error rate performance of the algorithm are documented.

In chapter 4, the KLMS algorithm as well as its normalized counterpart are described and implemented. The KLMS algorithms and the MMSE-based algorithm presented in chapter 3 are comprehensively compared and their efficiency verified in both slow fading and fast fading multipath channels.

Chapter 5 gives the conclusion of the thesis and future work.

1.6. Publications

1. M.B. Balogun, O.O. Oyerinde and S. H. Mneney, "Performance Analysis of the OFDM-IDMA System with Carrier Frequency Offset in a Fast Fading Multipath Channel," *in proceedings of IEEE 3rd International Conference on Wireless Communication Society, Vehicular Technology, Information Theory and Aerospace & Electronics Systems Technology, Global Wireless Summit 2013, Atlantic city, New jersey, USA,* 24th - 27th June 2013. (Global Wireless Summit 2013 Best Student Paper Award)

2. M.B. Balogun, O.O. Oyerinde and S. H. Mneney, "Linear MMSE-based Frequency Synchronization Algorithm for OFDM-IDMA Systems," *in Proceedings of IEEE AFRICON 2013, Mauritius, 9th -12th September 2013.*

3. M.B. Balogun, O.O. Oyerinde and S. H. Mneney, "Frequency Synchronization in OFDM-IDMA Systems using the Kernel Least Mean Square Algorithm," *in Proceedings of South Africa Telecommunication Networks and Applications Conference (SATNAC) 2013, Stellenbosch, South Africa, 1st - 4th September 2013.*

4. M.B. Balogun, O.O. Oyerinde and S. H. Mneney, "Adaptive Correction Algorithm for OFDM-IDMA Systems with Carrier Frequency Offset in a Fast Fading Multipath Channel," *Journal of Cyber Security and Mobility, vol. 2, No. 3&4, pp.201-220, 2014.*

5. M.B. Balogun, O.O. Oyerinde, and S. H. Mneney, "Carrier Frequency Synchronization for OFDM-IDMA Systems," *Submitted to SAIEE African Research Journal, under review (2013).*

CHAPTER 2

THE OFDM-IDMA MULTIUSER SYSTEM

2.1. Introduction

The multicarrier CDMA scheme, as discussed earlier, is largely limited by ISI and MAI. The IDMA scheme was proposed as a solution to the challenges confronting the MC-CDMA scheme. The proposed multicarrier IDMA scheme, which has been the focus of recent studies in wireless communications, is seen as a serious contender for the 4G and LTE cellular networks. Just as in the case of MC-CDMA, the multicarrier IDMA scheme is an OFDM-based hybrid multiuser scheme, which is a combination of the OFDM and the IDMA technique. The idea of combining OFDM with IDMA was to significantly improve the performance of the conventional IDMA system over multipath channels [20]. The combined scheme offers the advantages inherent in both OFDM and IDMA schemes and achieves a better performance than the MC-CDMA scheme, as studied in [19]. This section therefore gives a detailed review of the major studies on OFDM and the IDMA techniques.

2.2. Principles of OFDM

The orthogonal frequency division multiplexing technique dates back to about some four decades ago when a paper was published on the synthesis of band-limited orthogonal signals for multichannel data transmission by *Chang* [23], which was also patented in 1966. He proffered a principle where messages are transmitted via a linear band-limited channel without inter-carrier interference and inter-symbol interference. A year later, *Saltzberg* [24] presented a performance analysis of effective signal transmission in parallel form. There were other important contributions to OFDM in the following years by *Weinstein and Ebert* [25], *Peled and Ruiz* [26] among others, but OFDM, was first proffered as a wireless communication solution by *Cimini* in 1985 [27]. With the OFDM now realistic, practicable and widely accepted, it is now being employed in several wireless technologies and standards such as digital audio broadcasting (DAB), digital video broadcasting (DVB), high-rate wireless LAN standard [28, 29] (IEEE 802.11a) and the IEEE 802.16a metropolitan area network (MAN) standard.

In OFDM, high data rate streams are essentially divided into *N* parallel streams, each of a lower data rate, which are modulated by different sub-carriers while the symbol duration is being prolonged *N* times. The lower data rate streams are transmitted in parallel, over multiplexed subcarriers, which are mutually orthogonal. As long as orthogonality is maintained, there will be no interference between sub-carriers i.e. Inter carrier interference (ICI) and this will as well enable the receiver to separate signals carried by each sub-carriers [28].

Unlike the conventional Frequency Division Multiplexing (FDM) scheme, the spectra of the different modulated sub-carriers overlap in OFDM (Fig. 2-1b). This makes OFDM an appropriate scheme for optimum and efficient use of valuable spectrum. Also, the conversion of frequency-selective fading channel into a collection of parallel flat fading sub-channels simplifies the receiver structure of the OFDM system.

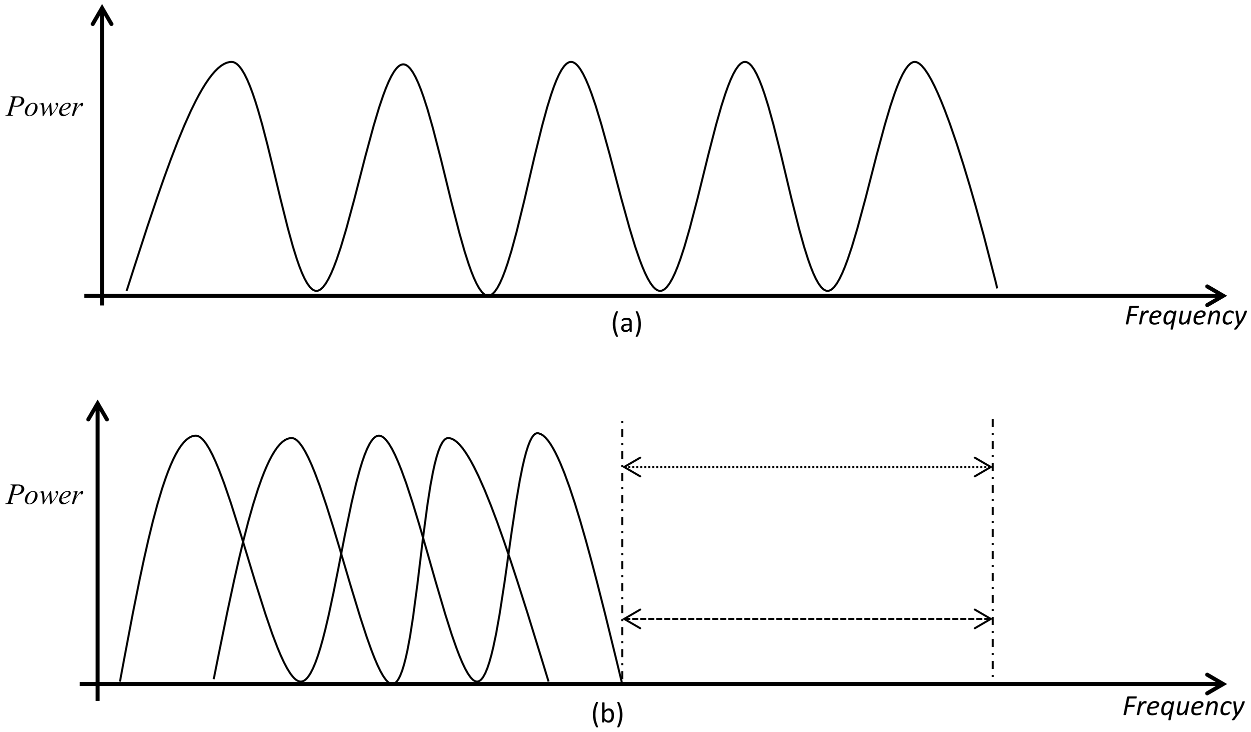

Fig. 2-1 Illustration of the spectrum-saving concept of the OFDM technique (b) compared with the regular FDM scheme (a)

Local Oscillators (LOs) were used earlier in OFDM implementation. However, the associated complexity and high cost, made real-life implementation unsuitable. The idea behind the analog implementation was extended to the digital domain by using the DFT and IDFT [25], being employed mainly to transform data between time domain and frequency domain. The introduction and the eventual use of the discrete Fourier transform and its inverse was a major breakthrough in OFDM implementation. In practice, however, OFDM systems are implemented using a combination of FFT and IFFT blocks that are mathematical equivalent versions of the DFT and IDFT, respectively, but more efficient to implement. Recent advances in very large scale integration technologies (VLSI) also have ensured an easy, cheap, and fast implementation using FFTs and IFFTs. In this approach, the data stream is divided into blocks of N symbols. Each block of data is then subjected to an IFFT and then transmitted. The immediate output of the IFFT has to be transmitted one at a time, hence, a parallel to serial conversion after the operation. This process, however, is reversed (i.e. serial to parallel conversion) and an inverse operation FFT is performed at the receiver [28].

Figure 2-2 illustrates in block diagram the adaptation of the IEEE standard 802.11a [29] for a baseband OFDM Transceiver. Each sub-carrier is modulated in phase and amplitude by the data bits in the OFDM system. One or more bits are being used in the modulation of each sub-carrier, depending on the kind of modulation method adopted (QPSK, 16/64 QAM, BPSK are most commonly used). Different coding schemes are used to achieve low SNR and to obtain better system efficiency. The encoded data stream is interleaved. This process involves assigning adjacent data bits to non-adjacent bits to reduce the burst symbol error. Interleaving reorders the data stream to avoid burst error. In the mapping process, modulated data are assigned to sub-carriers based on sub-carrier assignment information obtained from sub-carrier level sensing [30]. These are then serial-to-parallel converted and fed into the IFFT, which transforms the data from frequency domain to time domain. Each time-domain OFDM symbol is extended by the so-called cyclic prefix [31] or guard interval of Ng samples duration in order to combat inter-symbol interference. The samples of the guard interval are copied from the end of the time domain OFDM symbols as shown in Fig. 2-3. Typically, guard interval or the cyclic prefix of not more than 10% of the OFDM symbol's duration is employed though this is discarded at the receiver. Passing through the Digital-to-analog (DAC) converter, the signal is amplified and up-converted to desired center frequency before transmission in the frequency selective fading channel [32].

At the receiver, the CP symbols are removed after analog to digital conversion. A crucial synchronization process as indicated in Fig. 2-2 is carried out to estimate and correct carrier frequency offsets of the received signal as well as to find the symbol boundaries to prevent ISI and ICI. The FFT of the signal is taken before channel estimation is carried out to estimate the time and frequency domain response, in order to correctly detect and recover the transmitted data. The reverse of the other processes at the transmitter are executed at the receiver, as shown in Fig. 2-2, before the final process of decoding takes place in order to give the binary output signal [33].

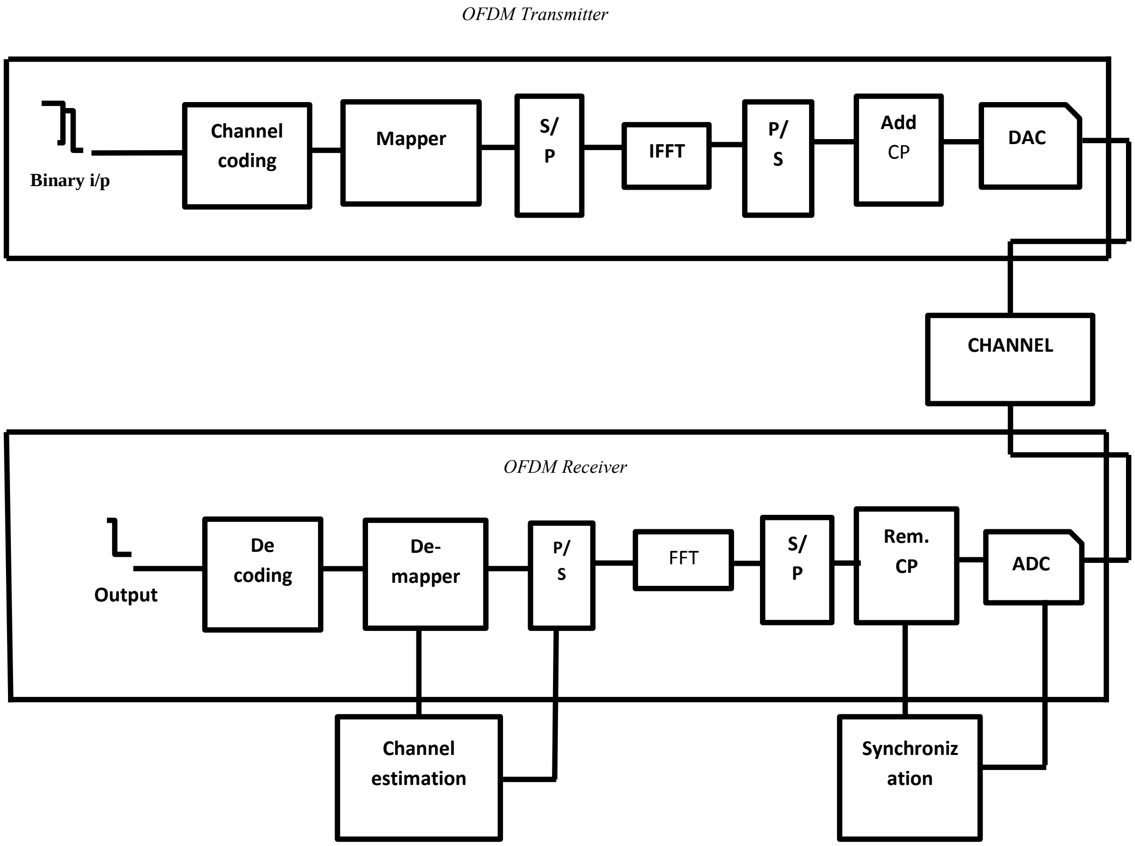

Fig. 2-2 Block diagram of a typical OFDM transceiver

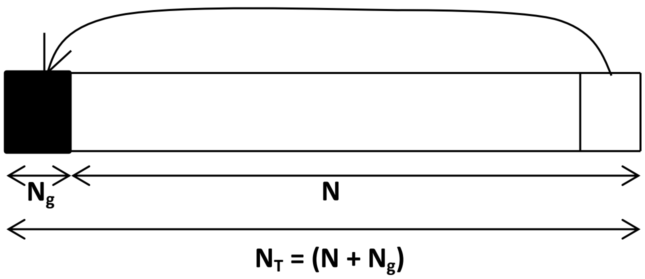

Fig. 2-3 Cyclic extension concept showing N sub-carrier OFDM signal with guard interval Ng.

2.3. Major Challenges in OFDM

Despite the laudable attributes of OFDM, which has informed its wide popularity as a modulation scheme for high-speed transmission, some major difficulties and drawbacks require effective handling and special attention to obtain the best operation possible out of this scheme. For the purpose of this review, three major issues that include; peak-to-average power ratio (PAPR), time and frequency synchronization and channel estimation, would be discussed.

2.3.1. Peak-to-average power ratio

Peak-to-average power ratio, which originates from the fact that an OFDM signal is the superposition of a number of modulated sub-carrier signals, is a scenario in OFDM where the peak amplitude of the emitted signal is considerably higher than the average amplitude [28]. This is a major drawback in OFDM systems, as it causes the analog-to-digital converter in the transmitter to be more complex while the efficiency of the power amplifier is reduced and the performance of the system degraded.

The peak-to-average power ratio of a transmitted signal $x(t)$ is given as the ratio of the maximum envelope power and average envelope power [34, 35], which can be expressed as

$$\beta = \frac{\max|x(t)^2|}{P_{avg}}, \tag{2.1}$$

where the average envelope power P_{avg}=$E|x(t)^2|$.

High PAPR implies that the high power amplifier (HPA) in an OFDM wireless system must have an efficiently used large linear range [35, 36]. Non-linearity of the HPA causes in-band distortion, which leads to an increase in the bit-error rate (BER) and also out-of-band emission (emission immediately outside the necessary bandwidth), causing interference with neighboring channels [30].

These drawbacks, therefore, have necessitated a search for a viable technique to combat PAPR. Several techniques have been proposed, to date, which include mainly; clipping and filtering [37, 38], coding [39], interleaver technique [40] and peak windowing [41]. In [42], the review of some major techniques is presented. In the review paper, it is stated that although the criteria for selecting a PAPR technique involves many aspects such as PAR reduction capacity, power increase, BER increase and complexity, a main consideration is that the cost of extra complexity for PAR reduction is lower than the cost of power inefficiency. In [40], a data randomization technique is presented, where it is submitted that by interleaving a data frame, the peaks in the associated OFDM signal can be compressed. In all of these techniques, PAPR reduction is basically carried out at the transmitter.

2.3.2. Channel Estimation

Before the demodulation of the OFDM signals at the transmitter, a reliable and accurate estimation of the channels is expedient, since the radio channel is frequency selective and time – varying in nature for wideband mobile communication systems [43]. Channel estimation is necessary for coherent symbol detection in an OFDM receiver.

Many techniques which include pilot-based technique, decision direct channel estimation and blind channel estimation techniques, have been proposed for a dynamic channel estimation with their own merits, demerits, and limitations. The blind channel estimation technique is studied in [44, 45]. In [46], block-type and comb-type pilot based channel estimation techniques are described. Also, [47] pointed out the downsides of previous works on channel estimation and proposed an efficient pilot tone placement scheme applicable to OFDM systems regardless of time variation in the channel. Recently, however, the Decision Directed Channel Estimation (DDCE) scheme was developed [48, 49]. The scheme employs both the pilot symbols as well as the detected message symbols for channel estimation. This gives it an edge over the previous pilot-based channel estimation techniques as the DDCE scheme benefits from the availability of about hundred percent pilot symbols, in the absence of symbol errors by employing the detected symbols in combination with the sparsely available pilot symbols [50].

2.3.3. Time and frequency offsets

Despite the robustness of OFDM against frequency selective fading channels, they are sensitive to timing and frequency offset errors. These cause Inter-symbol interference (ISI) and Inter-carrier interference (ICI), which degrade the bit-error-rate performance of the system considerably. Hence, time and frequency synchronization is pertinent for good performance of OFDM systems. However, it must be noted that any good synchronization scheme must primarily aim at maintaining low-complexity and fast synchronization convergence [51].

2.4. The IDMA Scheme

The IDMA technique as recently proposed is a multiuser scheme where interleavers serve as the sole means of distinguishing signals from different users at the receiver. The interleavers, which are randomly generated, are essentially different for each active user in the system [18]. The IDMA achieves all the inherent advantages of the CDMA such as dynamic channel sharing, robustness against multipath, system flexibility, and ease of cell planning [19]. The IDMA also offers improved capacity, and effectively combats MAI with low complexity, which is independent of the number of simultaneous users in the system. In a bid to achieve an enhanced cellular performance of the conventional IDMA over multipath, the OFDM-IDMA scheme was introduced in [20]. The combined OFDM-IDMA scheme therefore combats ISI and MAI effectively over multipath with low complexity and effectively supports high data rate transmission. The multicarrier scheme ensures a better cellular performance, higher diversity order, and spectral efficiency with associated low cost MUD [21].

2.4.1. The Transmitter Structure

The transceiver structure of the conventional IDMA scheme is shown in Fig. 2-4. The transmitter and the receiver structures of the OFDM-IDMA scheme is the same as the conventional IDMA structure plus the OFDM component as shown in Fig. 2-5. Considering the transmitter part of Fig. 2-5, with K users transmitting simultaneously, for anyone of the users denoted by k, the input data array is first encoded using a Forward Error Correction (FEC) code, generating a sequence $s_k \equiv \{s_k(1), \ldots., s_k(n), \ldots., s_k(N)\}^T$, where N represents the subcarrier length [52]. The low-rate FEC technique, which replaces the spreading operation carried out in MC-CDMA, is used for controlling errors in the input data propagation over the fading channel and to increase the coding gain of the multiuser system. Each of the chips $\{s_k\}$ are then assigned distinct interleavers represented as π_k. The assigned interleavers are randomly generated and a chip sequence $x_k \equiv \{x_k(1), \ldots., x_k(n), \ldots., x_k(N)\}^T$ results [52]. This process represents an important part of the multicarrier IDMA scheme, as the interleavers are the sole means of identifying different users in the system, ensuring ease of separation of signals coming from the various users at the receiver.

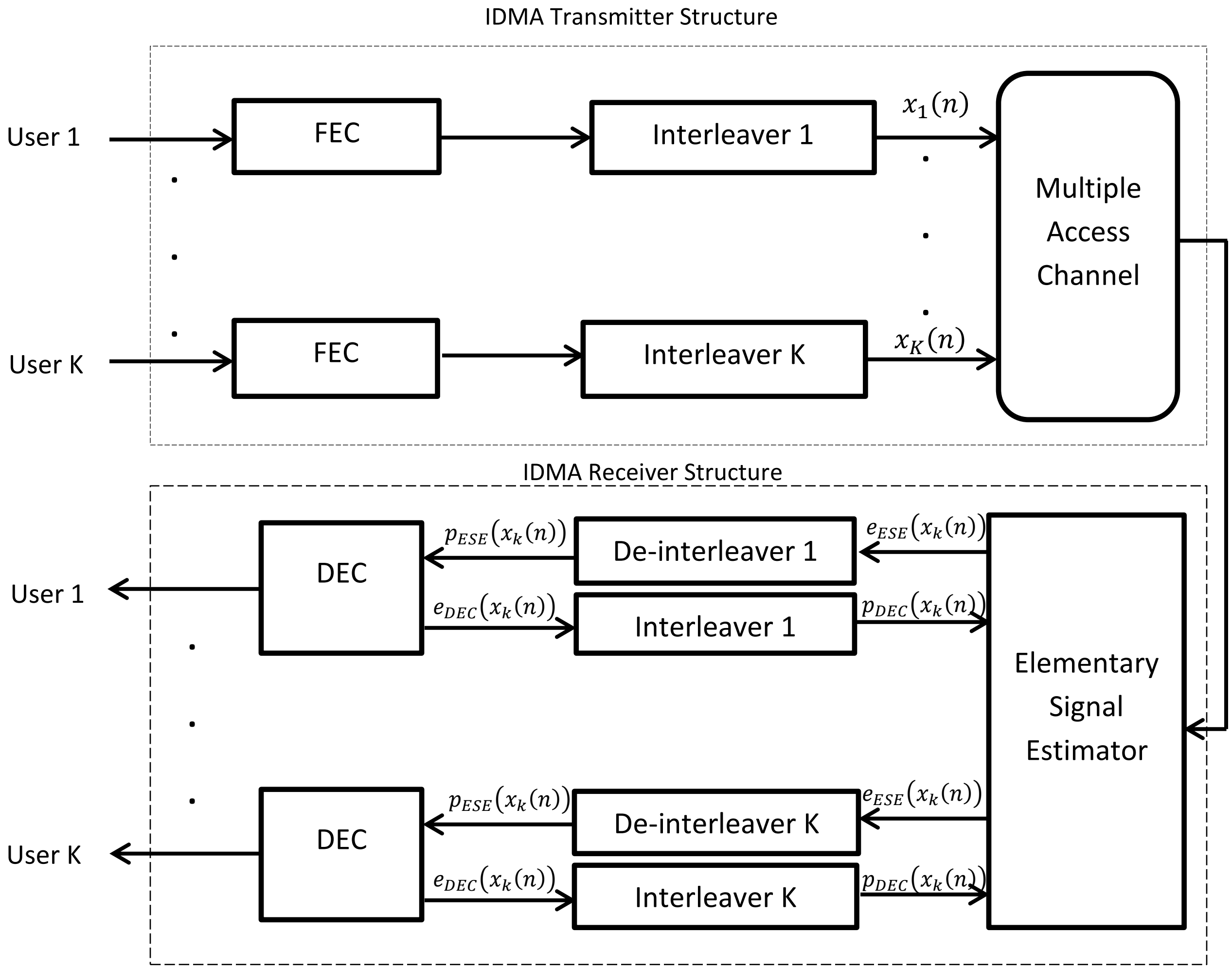

Fig. 2-4 Conventional IDMA Transceiver

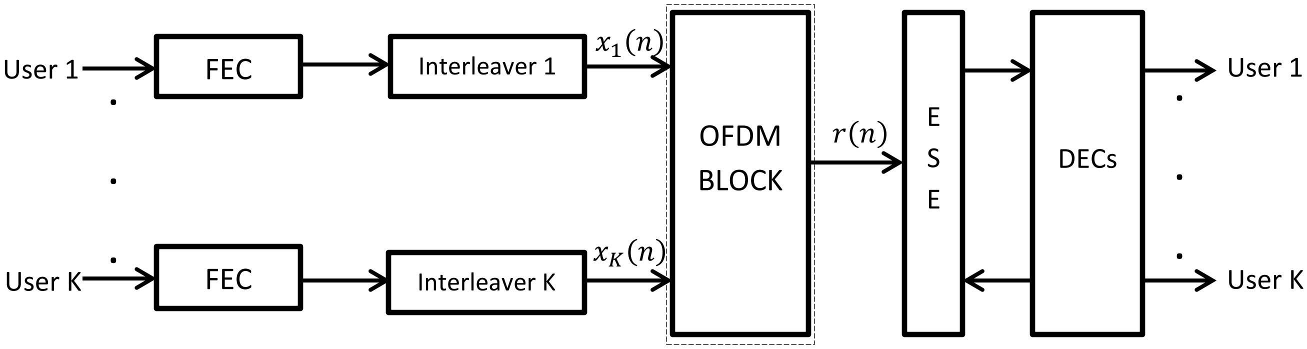

Fig. 2-5 OFDM-IDMA Transceiver

2.4.2. The Receiver Structure

The OFDM-IDMA scheme has a unique sub-optimal receiver structure [53], which consists mainly of the Elementary Signal Estimator (ESE) and *a posteriori probability* decoders (DECs). At the transmitter, the resulting sampled radio signal is transmitted over the multipath channel after the inverse fast Fourier transforms (IFFT) process, and the received signal is given as

$$r(n) = \sum_{k=1}^{K} x_k(n)h_k(n) + d(n), \tag{2.2a}$$

$$= x_k(n)h_k(n) + \beth_k(n), \tag{2.2b}$$

where $h_k(n)$, is the fading channel coefficient for an active user k, $d(n)$ is the additive white Gaussian noise with zero mean and variance σ^2. The symbol $\beth_k(n)$ represents the multiuser interference due to other users combined with the Gaussian noise $d(n)$, with respect to user k and can be expressed as

$$\beth_k(n) = \sum\nolimits_{k' \neq k} x_{k'}(n)h_{k'}(n) + d(n), \tag{2.3}$$

The ESE, which operates on a chip-by-chip order and *a posteriori probability* (APP) decoders are present at the receiver of system model for each active user k [54]. The presence of the ESE and the APP decoders represents a crucial aspect of the OFDM-IDMA process, which will be explained in detail.

2.4.3. The Elementary Signal Estimator and the APP Decoders

The ESE carries out a coarse chip-by-chip detection to roughly subtract the interference among the concurrent users in the multicarrier IDMA system. The chip-by-chip detection is of a very low computational cost and complexity [55]. The outputs of the ESE are the estimated probabilities of the transmitted signals, which are organized sequentially according to the simultaneous users and are fed to the APP decoders [55]. The mode of operation of the ESE and DECs is iterative, where extrinsic information is processed in a turbo-like mode between them. At the last iteration, the APP decoders give the hard decisions based on the refined estimations by the ESE and the logarithm likelihood ratio (LLR) estimate of the ESE and the APP decoders is obtained as [53]

$$p\big(x_k(n)\big) \equiv log\left[\frac{P_b(x_k(n) = +1)}{P_b(x_k(n) = -1)}\right]. \tag{2.4}$$

The outputs of both the ESE and the DECs above are probabilities of the values of the transmitted radio signals at the receiver [56], which will henceforth be stated as $p_{ESE}\big(x_k(n)\big)$ and $p_{DEC}\big(x_k(n)\big)$ depending on whether they are emanating from the ESE or the APP decoders at the receiver. Therefore, considering the fading channel represented by the coefficient h, the ESE employs the received signal $r(n)$ and the LLR for its operation, so that the resulting output is obtained as [53]

$$log\left[\frac{P_b(x_k(n) = +1|r(n), h)}{P_b(x_k(n) = -1|r(n), h)}\right] = log\left[\frac{P_b(x_k(n) = +1), h}{P_b(x_k(n) = -1), h}\right] + p_{ESE}\big(x_k(n)\big), \tag{2.5}$$

where the first part of the equation can be expressed as

$$e_{ESE}\big(x_k(n)\big) = log\left[\frac{P_b(x_k(n) = +1), h}{P_b(x_k(n) = -1), h}\right], \tag{2.6}$$

which is the extrinsic LLR about the transmitted signal $x_k(n)$ based on the characteristics of the fading channel and the *a priori* information of concurrent users in the system [53].

Considering the ESE chip-by-chip detection in a quasi-static multipath channel where the BPSK signaling is used and the transmitted signal $x_k(n)$ is treated as a random variable, $e_{ESE}\big(x_k(n)\big)$ is used to coarsely update the *a priori* LLR $p\big(x_k(n)\big)$, which is obtained from (2.4) as [53]

$$E\big(x_k(n)\big) = \left[\frac{exp(p_{ESE}(x_k(n))) - 1)}{exp\left(p_{ESE}\big(x_k(n)\big)\right) + 1)}\right] = tanh(p_{ESE}(x_k(n))/2), \tag{2.7}$$

$$Var\big(x_k(n)\big) = 1 - \Big(E\big(x_k(n)\big)\Big)^2, \tag{2.8}$$

where $E\big(x_k(n)\big)$ and $Var\big(x_k(n)\big)$ are the mean and variance of the transmitted signal $x_k(n)$ respectively. Using the central limit theorem, the interference $\beth_k(n)$ in (2.3) can be estimated by a Gaussian variable with mean and variance given as [53]

$$E\big(\beth_k(n)\big) = \sum_{k\prime \neq k}^{K} h_{k\prime}(n)\, E\big(x_{k\prime}(n)\big), \tag{2.9}$$

$$Var\big(\beth_k(n)\big) = \sum_{k\prime \neq k}^{K} |h_{k\prime}(n)|^2\, Var\big(x_{k\prime}(n)\big) + \sigma^2. \tag{2.10}$$

Applying the Gaussian estimation to the received signal in (2.2b), the output of the ESE in (2.6) is obtained as [53]

$$e_{ESE}\big(x_k(n)\big) = log\left[\frac{exp\left(-\dfrac{\big(r(n) - E\big(\beth_k(n)\big) - h_{k\prime}(n)\big)^2}{2Var\big(\beth_k(n)\big)}\right)}{\sqrt{2\pi Var\big(\beth_k(n)\big)}}\right],$$

$$= 2h_k(n).\frac{r(n) - E\big(\beth_k(n)\big)}{Var\big(\beth_k(n)\big)}, \tag{2.11}$$

$$= 2h_k(n).\frac{r(n) - E\big(r(n)\big) + h_k(n)E\big(x_k(n)\big)}{Var\big(r(n)\big) - |h_k(n)|^2.Var\big(x_k(n)\big)}, \tag{2.12}$$

The estimated mean and variance of the received signal based on (2.2) is therefore obtained as [53]

$$E\big(r(n)\big) = \sum_{k' \neq 1}^{K} h_{k'}(n)\, E\big(x_{k'}(n)\big), \tag{2.13}$$

$$Var\big(r(n)\big) = \sum_{k' \neq 1}^{K} |h_{k'}(n)|^2\, Var\big(x_{k'}(n)\big) + \sigma^2. \tag{2.14}$$

The key processes involved in the OFDM-IDMA chip-by-chip detection algorithm are given below.

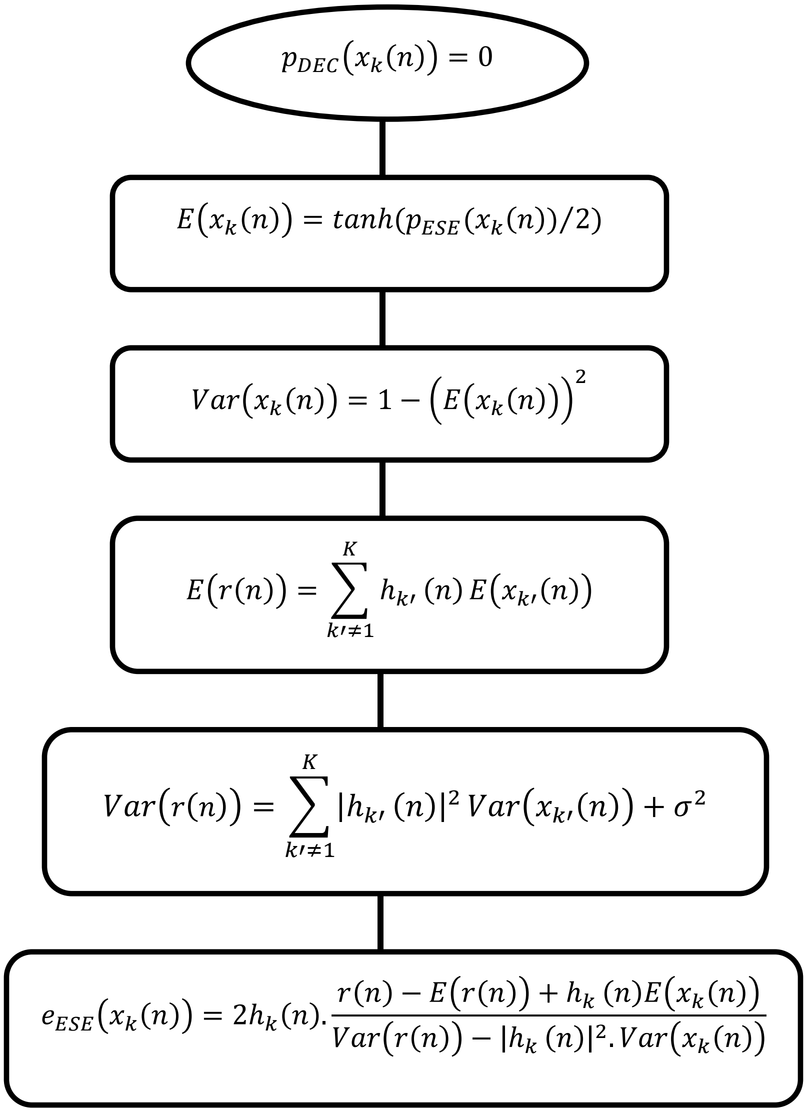

Fig. 2-6 Summary of the chip-by-chip detection

The DECs carry out APP decoding to update $p_{DEC}(x_k(n))$, and feedback the refined probabilities of the transmitted chips to the ESE for another round of iteration, to enable the ESE further improve its outputs [57].

2.5. Chapter Summary

This chapter introduced and reviewed the multicarrier IDMA multiuser scheme and the major studies pertaining to this scheme. The IDMA scheme, which was first introduced by *Li Ping et al* [18] and later improved upon by *Mahafeno et al* [20], was introduced to address ISI and MAI limitations of the multicarrier CDMA scheme. The OFDM technique, which forms the hybrid OFDM-IDMA scheme, has been discussed, pointing out the major challenges in this modulation technique. The concept of the multicarrier IDMA, which involves the assignment of distinct interleavers to different active users in the system, is discussed in detail. Also, the ESE function, which carries out a coarse chip-by-chip detection to roughly remove interference among users in the system, and the a posteriori probability (APP) based decoders have been examined and explained in detail. The ESE function and the APP decoders, which are present at the receiver end of the multicarrier IDMA system, enhance adequate separation of signals from different users for an improved multiuser detection.

CHAPTER 3

FREQUENCY SYNCHRONIZATION IN OFDM-IDMA SYSTEMS

3.1. Introduction

The OFDM-IDMA scheme offers an improved performance over the conventional IDMA scheme, and its main objective is to mitigate MAI and ISI over multipath channels, with low complexity [20]. The OFDM component in the system effectively combats ISI, but makes the system susceptible to synchronization errors. Thus, the OFDM-IDMA scheme becomes sensitive to synchronization errors due to the OFDM technique especially in the uplink channel, where different users are transmitting asynchronously, experiencing different levels of fading and delays. Most studies on OFDM-IDMA system assume perfect synchronization scenario, but this is not feasible in practice. Therefore, a comprehensive performance analysis on the OFDM-IDMA is in order, to verify the performance of the system in the presence of synchronization error. As stated earlier, the ISI caused by timing offsets is effectively addressed by the OFDM component, as the guard interval is made longer than the maximum channel delay spread. Hence, focus is on the more challenging impact of the carrier frequency offset error on the multicarrier IDMA scheme and a linear MMSE-based synchronization algorithm is presented to address the deteriorating effect of synchronization errors on the overall output of the system.

3.2. The Performance Analysis

The OFDM-IDMA scheme has been considered under ideal conditions. In practice, the scheme is subjected to synchronization errors, which reduce the overall performance of the system. Synchronization errors between the transmitter and the receiver of any mobile communication system increase the number of errors in the received bits of the radio signal. Carrier Frequency offset results mainly from two sources; mismatch between the transmitted and the received sampling clocks as well as the misalignment between the reference radio frequencies of the transmitter and receiver [58, 59]. The impact of carrier frequency offsets on OFDM-IDMA scheme was examined in [60] by Yong Liu et al. It was stated there, that the performance of the OFDM-IDMA scheme degrades with an increasing ratio between the maximum frequency offset and carrier spacing [60]. Also, a report on the OFDM-IDMA communication scheme with carrier frequency offsets is given in [61], focusing mainly on underwater acoustic channels (UWA). The sub-carriers in the OFDM component are essentially closely spaced in frequency compared to the spectrum bandwidth. Thus, the allowable frequency offset becomes a very small fraction of the available spectrum bandwidth [58, 62]. This makes the OFDM-IDMA system highly sensitive and maintaining sufficient open loop frequency accuracy therefore becomes difficult in the system, resulting in a significant Doppler shift [63, 64]. Carrier frequency offset errors cause inter-channel interference (ICI) and loss of orthogonality among the sub-carriers, leading to the overall performance degradation of the system.

Therefore, considering the practical situation where carrier frequency offsets (CFOs) are present in the OFDM-IDMA system, equation *(2.2b)* is modified as [65]

$$r_e(n) = \sum_{k=1}^{K} \big(x_k(n) h_k\,(n)\big) e^{\frac{j2\pi\varepsilon_k n}{N}} + d(n) \tag{3.1}$$

where n represents the sub-carrier index, N denotes the number of sub-carriers and ε_k, $\varepsilon_k \ll 0.5$ [66], symbolizes the CFO, normalized by the sub-carrier spacing. The discrete Fourier transforms (DFT) of the received signal in (3.1) can therefore be expressed as

$$R_e(m) = \sum_{n=0}^{N-1} r_e(n) e^{-j2\pi\varepsilon_k m/N}, \tag{3.2}$$

which can be further be expressed as,

$$R_e(m) = X_k(m) H_k(m) + \sum\nolimits_{k' \neq k} X_{k'}\,(m) H_{k'}(m) + \gamma_k(m) + \mathrm{D(m)} \tag{3.3}$$

The total interference in the OFDM-IDMA system in the presence synchronization error is obtained in the second part of (3.3) and this is denoted as $\text{ב}'_k(m)$, which is therefore given as

$$\text{ב}'_{\mathrm{k}}(\mathrm{m}) = \sum\nolimits_{k' \neq k} X_{k'}\,(m) H_{k'}(m) + \gamma_k(m) + \mathrm{D(m)} \tag{3.4}$$

where $\mathrm{D(m)}$ represents a Gaussian random variable which can be expressed as [67]

$$D(m) = \sum_{n=0}^{N-1} d(n) e^{-j2\pi n (m-\varepsilon_k)/N}. \tag{3.5}$$

Also, $\varrho_k(m)$ is the interference due to CFO between a specific user-k given as ε_k and another active user-k' in the system denoted as $\varepsilon_{k'}$. This can be represented mathematically as

$$\varrho_k(m) = \sum_{n=0}^{N-1} e^{j2\pi n(\varepsilon_{k'}-\varepsilon_k)/N}. \tag{3.6}$$

The interference in (3.6) can be further expressed as [60]

$$\varrho_k(m) = \sum_{n=0}^{N-1} \frac{sin(\pi\varepsilon_{k'})}{N\, sin(\pi(\varepsilon_{k'}-\varepsilon_k)/N)} . e^{j\pi(\varepsilon_{k'}-\varepsilon_k)(N-1)/N}. \tag{3.7}$$

Hence, the output of the elementary signal operator, in a multipath fading channel with carrier frequency offsets, based on the extrinsic log-likelihood ratios (LLRs) generation obtained in (2.11) and (2.12) becomes [16]

$$e'_{ESE}\big(X_k(m)\big) = 2H_k(m). \frac{R_e(m) - E\big(\beth'_k(m)\big)}{Var\big(\beth'_k(m)\big)}. \tag{3.8}$$

The estimated mean and variance of the received signal, in the presence of synchronization errors, based on (2.13) and (2.14) is therefore obtained as

$$E\big(R_e(m)\big) = \sum_{k'\neq 1}^{K} H_{k'}(m)\, E\big(X_{k'}(m)\big), \tag{3.9}$$

$$Var\big(R_e(m)\big) = \sum_{k'\neq 1}^{K} |H_{k'}(m)|^2\, Var\big(X_{k'}(m)\big) + \sigma^2. \tag{3.10}$$

The influence of the carrier frequency offset errors on the general output of the OFDM-IDMA system is therefore established in the derived equations. Errors due to CFOs in the system are crucial factors that cannot be neglected in practical situations, as they degrade the overall performance and efficiency of multicarrier systems [65]. Hence, it is imperative to draw up an effective synchronization algorithm to address the degrading influence of CFOs on OFDM-IDMA systems.

3.3. The MMSE-Based Synchronization Algorithm

This section presents a linear minimum mean-squared error (MMSE) approach, to mitigate the effect of CFOs in the OFDM-IDMA systems. The carrier frequency offset of a particular user can be compensated coarsely in the time domain of the system. But the main challenge is the residual CFOs due to multiple active users in the system, which results in inter-channel interference (ICI). Due to system configuration of the OFDM-IDMA scheme, the mitigation of the effect of the residual CFOs is executed after the fast Fourier transforms (FFT) process, in the frequency domain. The proposed MMSE-based synchronization algorithm is a non-data aided technique that centers on the mitigation of the ICI induced by the residual CFOs due to simultaneous users thereby, improving the overall output of the system. Hence, the linear MMSE-based synchronization algorithm is achieved following [68] by computing the second order statistics from (3.2), (3.5), and (3.7) as

$$E(|R_e(m)|^2) = \tfrac{1}{N} E\left(\left|\textstyle\sum_{n=0}^{N-1}\big(x_k(n) \otimes h_k(n)\big) e^{\frac{j2\pi\varepsilon_k n}{N}} e^{-\frac{j2\pi\varepsilon_k m}{N}}\right|^2\right) + E(|D(m)|^2), \tag{3.11}$$

$$= \frac{1}{N}\sum_{m=0}^{N-1}\sum_{n=0}^{N-1} E\big((x_k(m) \otimes h_k(m))(x_k(n) \otimes h_k(n))^*\big)$$

$$.\, e^{-j2\pi\varepsilon_k(m-n)/N} + N_0/2, \tag{3.12}$$

$$= \frac{1}{N}\sum_{m=0}^{N-1}\sum_{n=0}^{N-1} .\left[\sum_{l=0}^{N-1} E(|H_l|^2) E(|X_l|^2) e^{j2\pi l(m-n)/N}\right]$$

$$.\, e^{-j2\pi\varepsilon_k(m-n)/N} + N_0/2, \tag{3.13}$$

$$= Q_s|H|^2 + N_0/2, \tag{3.14}$$

where the data symbol energy is denoted as $\mathrm{Q_s}$, $\mathrm{N_0}/2$ represents the power spectral density and the discrete convolution operator $\otimes$ can be stated as [68]

$$\mathrm{b_n} \otimes \mathrm{g_n} = \sum_{\mathrm{l}=0}^{\mathrm{N}-1} \mathrm{b_l g_{n-l}}, \tag{3.15}$$

for the arrays $\mathrm{b_n}$ and $\mathrm{g_n}$ with sub-carrier length *l*, $|\mathrm{H}|^2 \equiv \mathrm{E}(|\mathrm{H_l}|^2)$, n = 0, 1, 2, …, N-1.

The power of the ICI term can therefore be derived from eqns. (3.3) and (3.14) as shown below

$$E(|\varrho_k(m)|^2) = E(|R_e(m)|^2) - E(|\ D(m)|^2) - E(|X_k(m)H_k(m)|^2)sinc^2(\varepsilon_k) \qquad (3.16)$$

$$= Q_s|H|^2\big(1 - sinc^2(\varepsilon_k)\big) \qquad (3.17)$$

The influence of the carrier frequency offset ε_k is apparent in (3.17) and the ICI power has the smallest value when the carrier frequency offset $\varepsilon_k = 0$. Also from (3.17), the significance of the ICI power increases with an increasing value of the carrier frequency offset. Hence, the reduction of the spectral power of the ICI can mitigate the influence of synchronization errors and will significantly compensate for the carrier frequency offset errors due to the residual CFOs of the multiple active users in the OFDM-IDMA system. Therefore, to reduce the spectral power of the ICI at the receiver end of the OFDM-IDMA system, the following cost function, is employed [68, 69]

$$J_c(m) = \frac{1}{M}\sum_{k=0}^{M-1} E((|R_e(m)|^2 - G^2)^2), \qquad (3.18)$$

where G^2 is a positive real constant chosen to ensure the cost function $J_c(m)$ is minimized for $\varepsilon_k = 0$. Equation (3.18) can be further expanded as

$$J_c(m) = \frac{1}{M}\sum_{k=0}^{M-1} E(|R_e(m)|^4) - \frac{1}{M}\sum_{k=0}^{M-1} E(|R_e(m)|^2.2G^2) + (G^2)^2. \qquad (3.19)$$

The second term of (3.19) above is independent of the carrier frequency offset as derived in (3.3), hence, the gradient of $J_c(m)$ with respect to ε_k can be obtained and the stochastic update error signal may be expressed mathematically as [68]

$$\text{ȩ}(m) = \frac{1}{M}\sum_{k=0}^{M-1} |R_e(m)|^2 . Re\left(R_e{}^*(m)\frac{\partial}{\partial \varepsilon_k}R_e(m)\right). \qquad (3.20)$$

Equation (3.20) is employed to update the carrier frequency-tracking loop in the system, where $\frac{\partial}{\partial \varepsilon_k}R_e(m)$ is expressed as

$$\frac{\partial}{\partial \varepsilon_k}R_e(m) = \frac{1}{\sqrt{N}}\sum_{n=0}^{N-1}\left(r_e(n).j\frac{2\pi n \varepsilon_k}{N}\right).e^{-j2\pi nk/N}. \qquad (3.21)$$

However, to reduce the complexity of the system model, the update error signal in (3.20) is approximated and streamlined to obtain the following expression [68]

$$\text{ȩ}^{App} = \frac{1}{M}\sum_{k=0}^{M-1} |R_e(m)|^2 \, Re(R_e{}^{*}(m).\left(R_e(m+1) - R_e(m-1)\right). \qquad (3.22)$$

Equation (3.22) therefore gives the approximated error update signal, which is used to update the carrier frequency-tracking loop in the OFDM-IDMA system. Low complexity implementation of the synchronization algorithm is achieved in (3.22) to combat the influence of the ICI induced by the simultaneous users. Thus, the overall system output and performance of the OFDM-IDMA system is significantly improved.

3.4. Simulations and Discussion

Computer simulations are carried out to analyze, and verify the performance of the OFDM-IDMA system with CFO in a fading multipath channel scenario. All simulation results are presented based on the BER performance of the system in a Rayleigh fading multipath channel of M = 16 paths. The Rayleigh channel is employed, as it represents more precisely the distortion that emanates from the multipath signals during data transmission [70]. The QPSK modulation technique is employed, with operating carrier frequency of 2GHz and sampling period of 0.5µs. The system model used has the input data length set at 32, spreading length 4, with randomly generated interleavers. The number of sub-carriers, which is assumed the same for all users, is set at N=128 bits and the number of samples in the guard interval is set at 7 with iteration of 4. The general performance of the system is investigated at a constant multipath fading scenario with mobile speed v= 15 km/h. Also, simulations are carried out to validate and establish the performance of the proposed linear MMSE-based synchronization algorithm. The simulation results are presented based on the bit error rate (BER) performance of the system in a Rayleigh fading multipath channel with normalized Doppler frequencies of fD*n* = 0.0136, fD*n* = 0.1085 and fD*n* = 0.1808 corresponding to mobile speeds of v= 15km/h, v = 120km/h and v = 200km/h respectively.

In Fig. 3-1, the performance of the OFDM-IDMA system model in the presence of carrier frequency offset errors is shown. As demonstrated in [60], the OFDM-IDMA system is sensitive to carrier frequency offsets. Values of CFOs are varied from zero, which represents the ideal situation where the system is perfectly synchronized, up to a high CFO value of 0.17. Carrier frequency offset values are assumed based on different techniques presented by *Morelli et al.* in [71] for carrier frequency offset estimation. Thus, CFOs are assumed to be known for all concurrent users in the system model. The simulation is implemented in a Rayleigh fading multipath channel with a constant mobile speed of 15 km/h. From the plot, the performance of the OFDM-IDMA system model is not significantly influenced by a small value of carrier frequency offset at CFO = 0.02. However, as the CFO value increases up to CFO = 0.17, a significant degradation is experienced. The BER degrades with increase in SNR, and further increase in CFO value will only lead to a greater deterioration in the system output. Thus, as the value of the CFO increases, the system experiences greater degradation in its overall output and efficiency.

The plot in Fig. 3-2 shows the effect of increasing mobile speed on the OFDM-IDMA system in a fading Rayleigh multipath channel. The performance of the multicarrier IDMA system is affected as the mobile speed is varied, even in the absence of CFO. However, it can be seen from the plot that at CFO=0.1, with the mobile speed also increasing in a fast fading Rayleigh channel scenario, there is a significant deterioration in the performance of the multicarrier system.

Fig. 3-3 shows the bit error rate performance of the OFDM-IDMA system upon the application of the linear MMSE-based correction algorithm. The plot shows the impact of the proposed algorithm on the system model in the presence of high CFOs of 0.1 and 0.17. The synchronization algorithm is implemented in the presence of high carrier frequency offsets to undoubtedly demonstrate its effectiveness. There is a significant reduction and substantial mitigation of the carrier frequency offset errors, signifying an effective decrease in the power of the ICI due to the residual CFOs of simultaneous users in the multicarrier IDMA system.

Moreover, the performance of the OFDM-IDMA system in a fading multipath channel of varying mobile speed is established in Fig. 3-4. The mobile speed is varied at 15 km/h, 120 km/h, and 200 km/h while the value of the carrier frequency offset is fixed. The overall bit-error rate performance and output of the system degrades as the mobile speed increases. The algorithm is applied in a fast fading multipath scenario to further ascertain its efficiency in real life situations. Thus, the implemented MMSE-based algorithm is able to mitigate the deteriorating influence of carrier frequency offset error on the system, even in a fast fading multipath channel with varying mobile speed. Furthermore, the algorithm is applied to a multicarrier IDMA system with varying number of concurrent users as shown in Fig. 3-5, in a fast fading Rayleigh channel of mobile speed set at 120 km/h. Substantial improvement in the overall cellular output is achieved which validates the effectiveness of the algorithm.

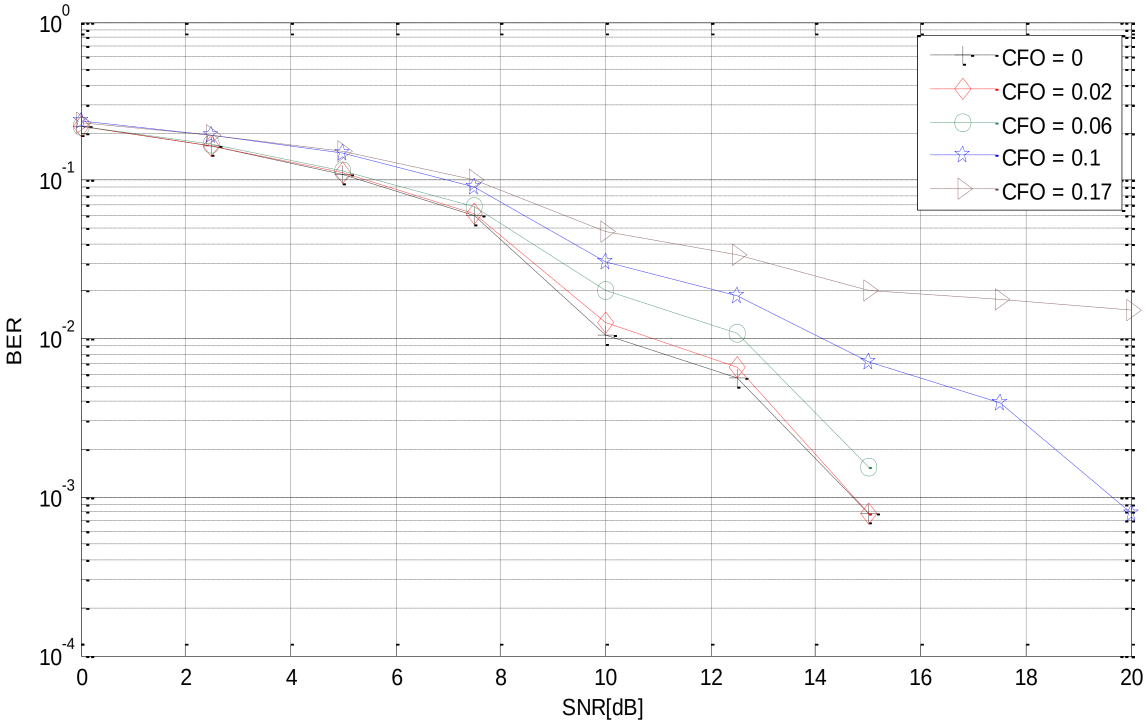

Fig. 3-1 The general performance of the OFDM-IDMA system model with increasing CFOs from 0 to 0.17

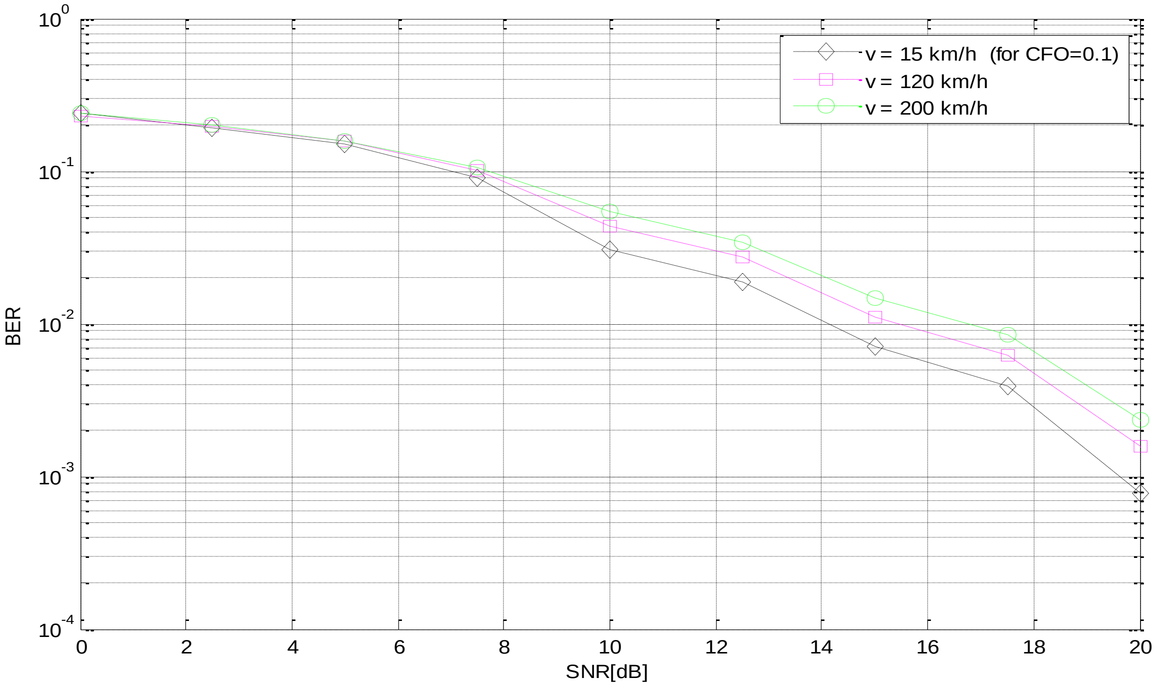

Fig. 3-2 OFDM-IDMA System model performance with increasing mobile speed at CFO=0.1

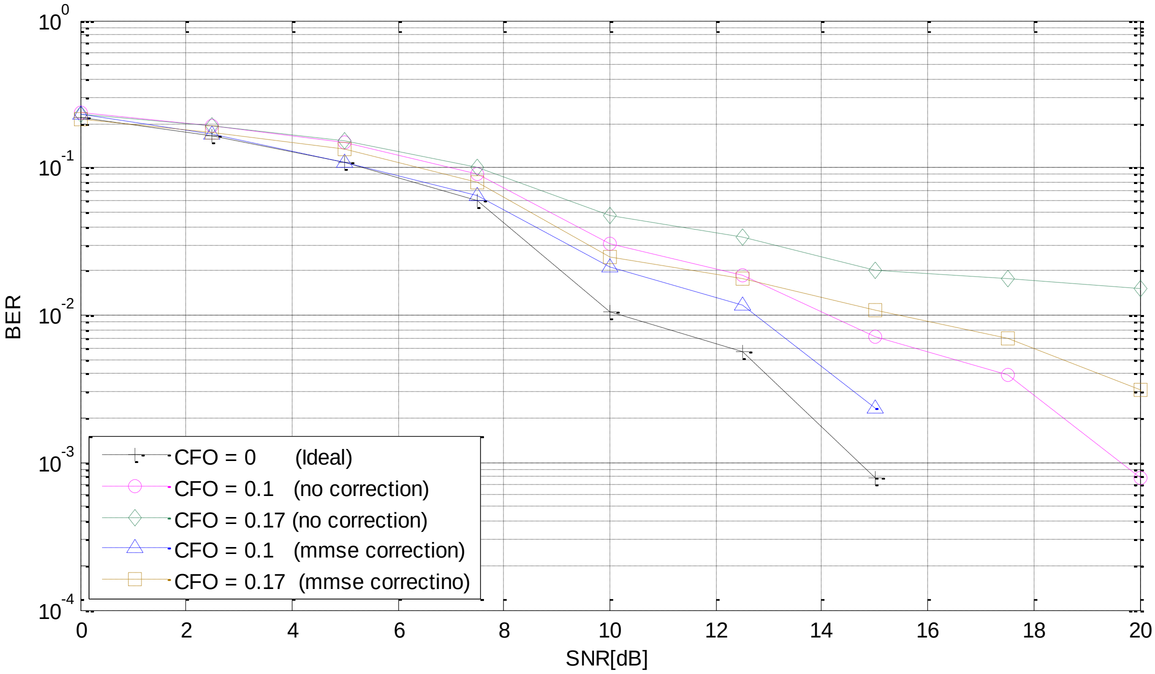

Fig. 3-3 The impact of the proposed linear MMSE-based synchronization algorithm on the OFDM-IDMA system model with carrier frequency offsets 0.1 and 0.17

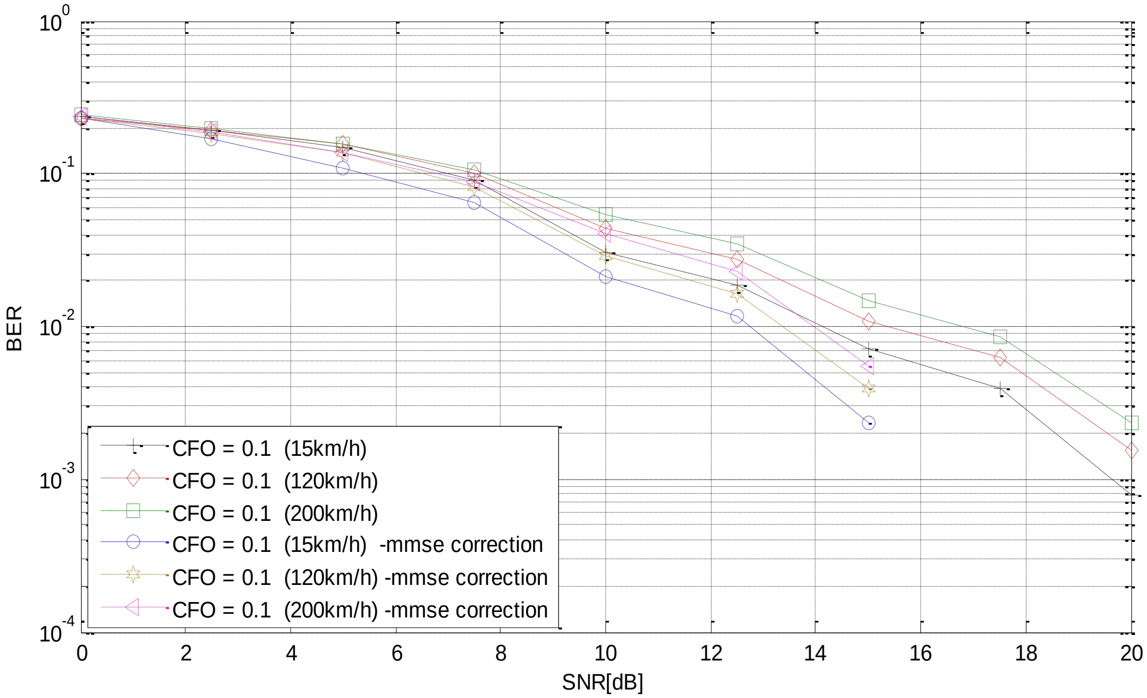

Fig. 3-4 BER performance of the OFDM-IDMA system model with the proposed algorithm in a fast fading multipath channel with increasing mobile speeds 15 km/h, 120 km/h and 200 km/h

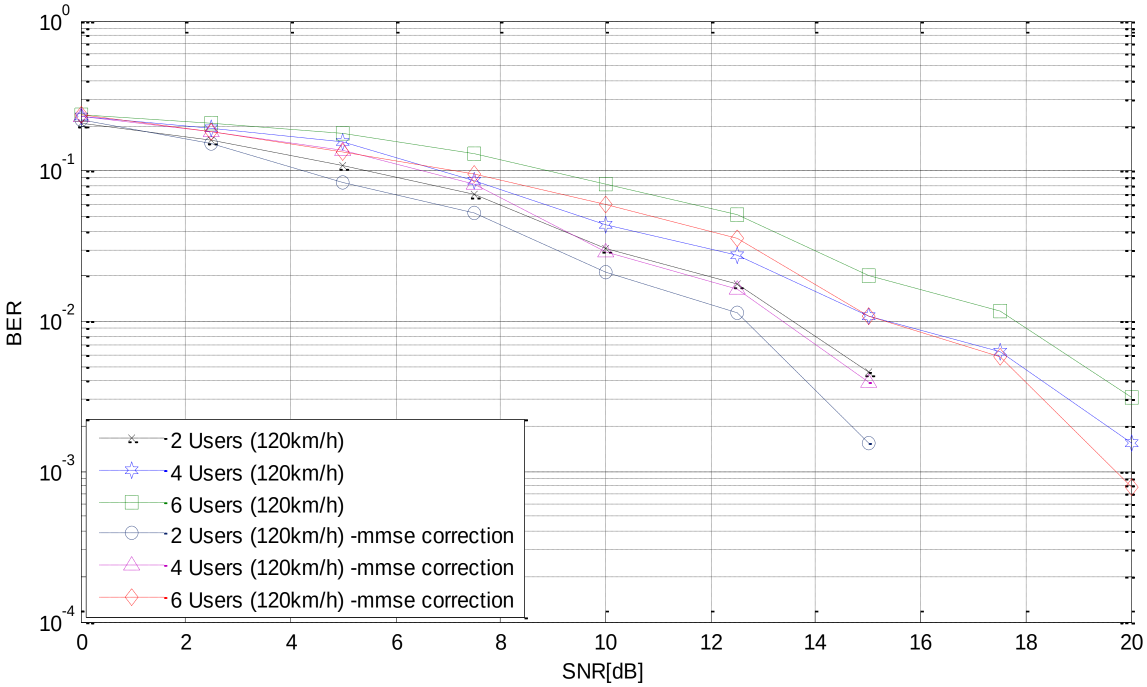

Fig. 3-5 BER performance of the proposed algorithm with varying number of users and mobile speed set at 120 km/h

3.5. Chapter Summary

In this chapter, the OFDM-IDMA scheme has been investigated in the presence of carrier frequency offset errors. The OFDM component was introduced into the multicarrier IDMA scheme to address ISI in the system. However, the technique comes with its inherent drawback of sensitivity to synchronization errors. A performance analysis to ascertain and analyze the impact of synchronization errors in the OFMD-IDMA scheme has therefore been carried out. The presence of CFOs in the system degrades the overall performance of the multicarrier scheme and this must be addressed to get the best out of this noble scheme. A linear MMSE-based synchronization algorithm is therefore proposed and implemented to mitigate the deteriorating influence of synchronization errors in the system. Although the carrier frequency offset of a specific user can be compensated coarsely in the time domain, the challenge posed by the residual CFOs from other active users remains. This causes ICI in the system thereby reducing the efficiency of the multicarrier scheme. Hence, the algorithm focused on the mitigation of the power of the ICI induced by other active users in the system.

Simulation results, which verify the deteriorating impact of synchronization errors on the overall performance of the system, are presented. Also, computer simulation results show that the proposed synchronization algorithm has a substantial influence on the system and significantly mitigates the impact of synchronization errors on the performance of the system. The algorithm was further applied in a fast fading multipath channel scenario to ascertain its effectiveness. Results show a significant improvement on the output of the multicarrier system.

CHAPTER 4

THE KLMS SYNCHRONIZATION ALGORITHMS

4.1. Introduction

This section presents a more effective synchronization algorithm, which employs the Kernel Least Mean Square (KLMS) method, to correct the degrading influence of synchronization errors on the OFDM-IDMA systems. This method has not been exploited, to the best of our knowledge, to combat carrier frequency offset errors in multicarrier IDMA systems. The central logic behind the KLMS synchronization algorithm is to execute the conventional Least Mean Square (LMS) algorithm in the kernel space [72]. The modulated input signal is used in the implementation of the kernel function, which enhances the efficacy of the algorithm and the overall output of the multicarrier system. The synchronization process for the OFDM-IDMA system model is executed after the fast Fourier transforms (FFT), in the frequency domain.

4.2. The Kernel Least Mean Square Algorithm

Owing to the Doppler shift and the mismatch, which arise between the carrier frequencies at the transmitter and the receiver of the multicarrier system, carrier frequency offset errors occur. These significantly cause degradation in the overall output of the system. The KLMS algorithm is therefore adapted and implemented to correct the ICI caused by the CFOs in the OFDM-IDMA system. The LMS algorithm, which has been utilized in various applications in communications and signal processing, is recognized for its simplicity. The KLMS algorithm, which inherits this simplicity is realized at low complexity and the coefficient vector of the algorithm is updated according to the expression defined as [72]

$$L(n+1) = L(n) + 2\mu \times \text{ȩ}(n) \times \aleph\big(x_k(n)\big), \tag{4.1}$$

where $L(n)$ is the coefficient vector, μ is the step-size and the mapping procedure is achieved by the vector function $\aleph\big(x_k(n)\big)$. The update error signal $\text{ȩ}(n)$, which is very central to the execution of the algorithm, is obtained as

$$\text{ȩ}(n) = r(n) - r_e(n), \tag{4.2}$$

where $r(n)$ represents the desired signal and from (3.1), $\mathrm{r_e(n)}$ is the received signal in the presence of CFOs. Hence, the error signal is used to update the carrier frequency-tracking loop, and the expected output is expressed as [72]

$$y(n) = [L(n), \aleph(x_k(n))]. \tag{4.3}$$

Therefore, with sufficient knowledge of the input data by the receiver and the update error signal obtained, the deteriorating influence of the CFOs can effectively be corrected for the active users in the multicarrier system.

The non-recursive form of (4.1) is stated mathematically as [72]

$$L(n) = L(0) + 2\mu \textstyle\sum_{i=0}^{N-1} \text{ȩ}(i)\aleph(x'_k(n)). \tag{4.4}$$

From (4.3) and (4.4), initializing $L(0) = 0$, $y(n)$ is derived as:

$$y(n) = 2\mu \textstyle\sum_{i=0}^{N-1} \text{ȩ}(i)[\aleph(x'_k(n)), \aleph(x_k(n))]. \tag{4.5}$$

The expected output in terms of the update error signal, employing the Kernel method is therefore expressed as

$$y(n) = 2\mu \textstyle\sum_{i=0}^{N-1} \text{ȩ}(i)\text{Ƙ}(\mathrm{x_k(n), x'_k(n)}). \tag{4.6}$$

where Ƙ is the Kernel function, which is given as [73]

$$\text{Ƙ}\left(\mathrm{x_k(n), x'_k(n)}\right) = \exp\left(-\frac{||\mathrm{x_k(n) - x'_k(n)}||^2}{\gamma^2}\right). \tag{4.7}$$

where γ is the kernel width parameter.

However, for an enhanced system tracking and amplitude stability, the normalized KLMS (NKLMS) is presented. The NKLMS helps to stabilize the step-size parameter so that $L(n+1)$ controls better and minimizes error in the system [72]. Thus, from (4.1),

$$L(n+1) = L(n) + \frac{2\mu}{[\aleph(x'_k(n)), \aleph(x_k(n))]} . \text{ȩ}(n) \times \aleph(x_k(n)). \tag{4.8}$$

Similar to (14),

$$L(n) = L(0) + 2\mu \textstyle\sum_{i=0}^{N-1} \text{ę}(i) \frac{\aleph\left(x'_k(n)\right)}{[\aleph(x'_k(n)),\aleph(x_k(n))]}. \tag{4.9}$$

Initializing $L(0) = 0$ with no *a priori* information available [74],

$$L(n) = 2\mu \sum_{i=0}^{N-1} \text{ę}(i). \frac{\aleph\left(x'_k(n)\right)}{[\aleph\left(x'_k(n)\right), \aleph\left(x_k(n)\right)]}. \tag{4.10}$$

Thus, from (4.3) and (4.10), $y(n)$ is derived as

$$y(n) = 2\mu \sum_{i=0}^{N-1} \text{ę}(i) \frac{\aleph\left(x'_k(n)\right)}{[\aleph\left(x'_k(n)\right), \aleph\left(x_k(n)\right)]} . \aleph\left(x_k(n)\right). \tag{4.11}$$

The derivation above therefore gives the expression for the normalized KLMS. Hence, with the knowledge of the modulated signal at the receiver end of the system and the update error signal as derived, the degrading influence of the synchronization errors is effectively corrected.

4.3. Simulations and Discussion

The performance of the KLMS algorithm as well as the normalized KLMS algorithm is shown through computer simulations. The results from the computer simulations are presented in terms of the bit error rate performance of the OFDM-IDMA system model used. The algorithms are also compared, and analyzed jointly. Furthermore, the BER performance of the two algorithms are compared with the linear MMSE-based synchronization algorithm discussed in chapter 3 and the achievable performances of these algorithms, in a Rayleigh multipath channel scenario with varying mobile speed, are documented. Adopting the QPSK modulation technique, the OFDM-IDMA system model operates at a carrier frequency of 2GHz in a Rayleigh fading multipath channel of M= 16 paths with spreading sequence [+1, -1, +1, -1, ..] for all users. The input data length is set at 32, spreading length 4, with randomly generated interleavers and sampling period of 0.5µs. The number of sub-carriers is set at N=128 for all users, with the number of samples fixed at 7 for the guard interval. The performance of the system model in terms of the bit error rate is also documented in a Rayleigh channel with normalized Doppler frequencies of *fDn* = 0.0136, and *fDn* = 0.1808 which corresponds to mobile speeds of v= 15 km/h, and v = 200 km/h respectively. The simulation carried out with varying mobile speed demonstrates the performance of the proposed algorithm in both fast and slow fading multipath channels.

From the previous chapter, the impact of CFOs on the performance of the multicarrier IDMA system has been clarified. The introduction of the OFDM component makes the system susceptible to synchronization errors. The ideal OFDM-IDMA scenario in which an error free system is assumed (i.e. CFO=0), is included as a clear benchmark in the simulations to visibly demonstrate the impact of synchronization errors on the system as well as the subsequent influence of the various synchronization algorithms on the general output of the multicarrier system.

Fig. 4-1 shows the plot from the implementation of the KLMS synchronization algorithm. The algorithm works in accordance with the Kernel matrix, which is achieved by the inner products of the input samples using the Kernel function [75]. The step size for the algorithm is set at $\mu = 0.5$ for optimum performance and reasonable convergence [76]. The plot in Fig. 4-1 shows the influence of the algorithm on the system model with CFOs 0.05 and 0.1. At CFO=0.05, a comprehensive correction is attained as seen from the plot. At a higher CFO of 0.1, a conspicuous and significant improvement in the BER performance is also achieved.

The MMSE-based synchronization algorithm, as discussed in the previous chapter is compared with the KLMS algorithm in Fig. 4-2. As seen from the plot, the KLMS achieves a better synchronization than the MMSE-based algorithm. The influence of the two algorithms on the output of the system is also evident at a higher CFO value of 0.1, although the KLMS achieves an improved system performance.

The influence of the MMSE-based algorithm and the KLMS algorithm is further verified as shown in Fig. 4-3, in a Rayleigh fading channel with varying mobile speed of 15 km/h, which represents the slow fading scenario and 200 km/h for fast fading, while the CFO value is fixed at 0.1 depicting a more practical situation. The algorithms show visible influence on the performance of the system and even in a fast fading multipath scenario, the effect of these algorithms is still very much significant.

Fig. 4-4 shows the comparison of the KLMS algorithm shown in Fig. 4-1 and that of the improved normalized KLMS algorithm. The NKLMS brings stability into the system as well as an improved overall performance. As seen from the plot, the NKLMS even outperforms the regular KLMS in both cases (i.e. CFO=0.05 and CFO=0.1) although this is more visible at a higher CFO value of 0.1. Also, both algorithms are implemented at a varying mobile speed of 15km/h and 200 km/h with CFO =0.1 as shown in Fig. 4-5 for better comparison. From the plot, the NKLMS offers a better and improved output.

Finally, the MMSE-based algorithm, the KLMS algorithm and its normalized counterpart, are implemented and compared, in Fig. 4-6. As discussed earlier, the plot ascertains the trend, which shows that the MMSE-based algorithm has the least impact on the system while the NKLMS exceeds the other algorithms in performance. In terms of computational complexity, the discrete-time derivation [77, 78], is employed in the implementation of the MMSE-based algorithm to obtain the stochastic update signal in (3.23) with computational complexity of $O(N^2)$. However, the KLMS algorithms which are of computational complexity $O(N)$ [79], ensure significant overhead is not added to the overall multicarrier system complexity. The KLMS algorithms therefore offer better and improved synchronization in the system although the NKLMS is more desirable and efficient, as it attains a significant and more improved BER output.

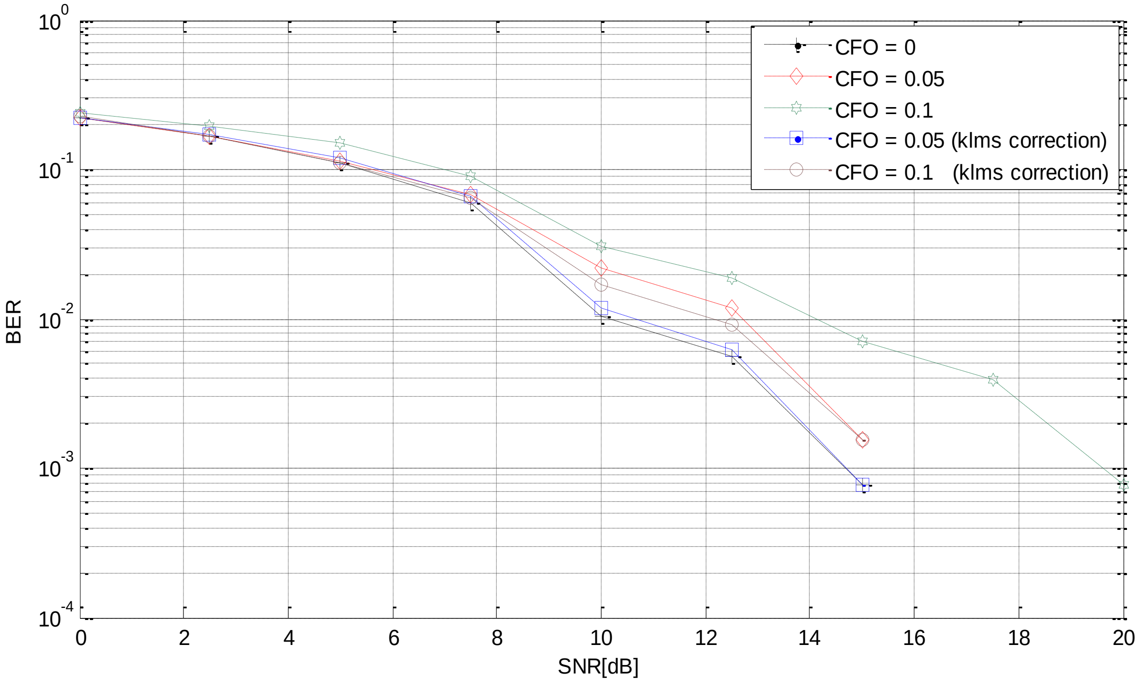

Fig. 4-1 The impact of the KLMS synchronization algorithm on the OFDM-IDMA system model with carrier frequency offsets 0.05 and 0.1

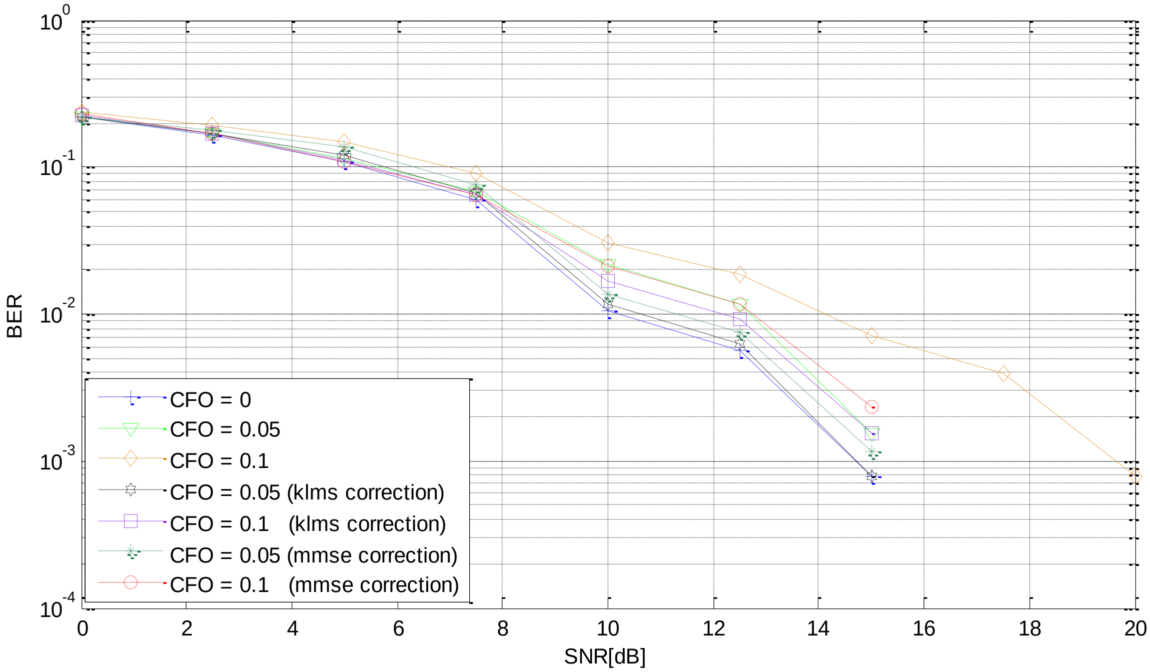

Fig. 4-2 Performance of the MMSE and the KLMS synchronization algorithms on the OFDM-IDMA system model with carrier frequency offsets 0.05 and 0.1

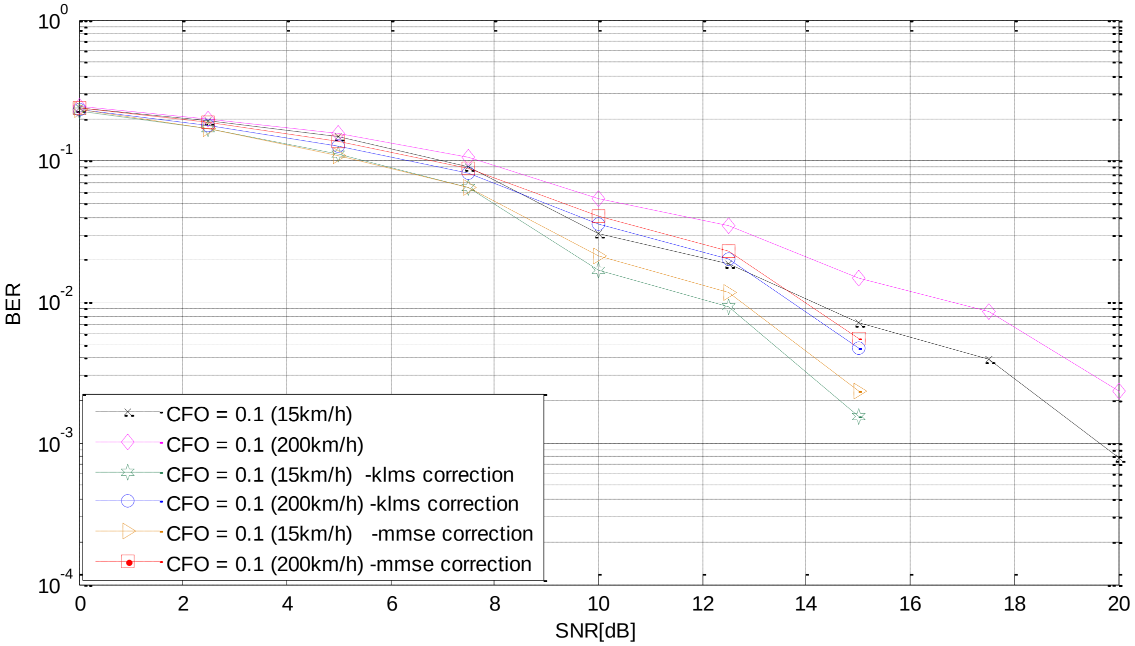

Fig. 4-3 BER performance of the multicarrier IDMA system with the MMSE and the KLMS algorithms in both slow and fast fading multipath channel of mobile speeds 15 km/h, and 200 km/h

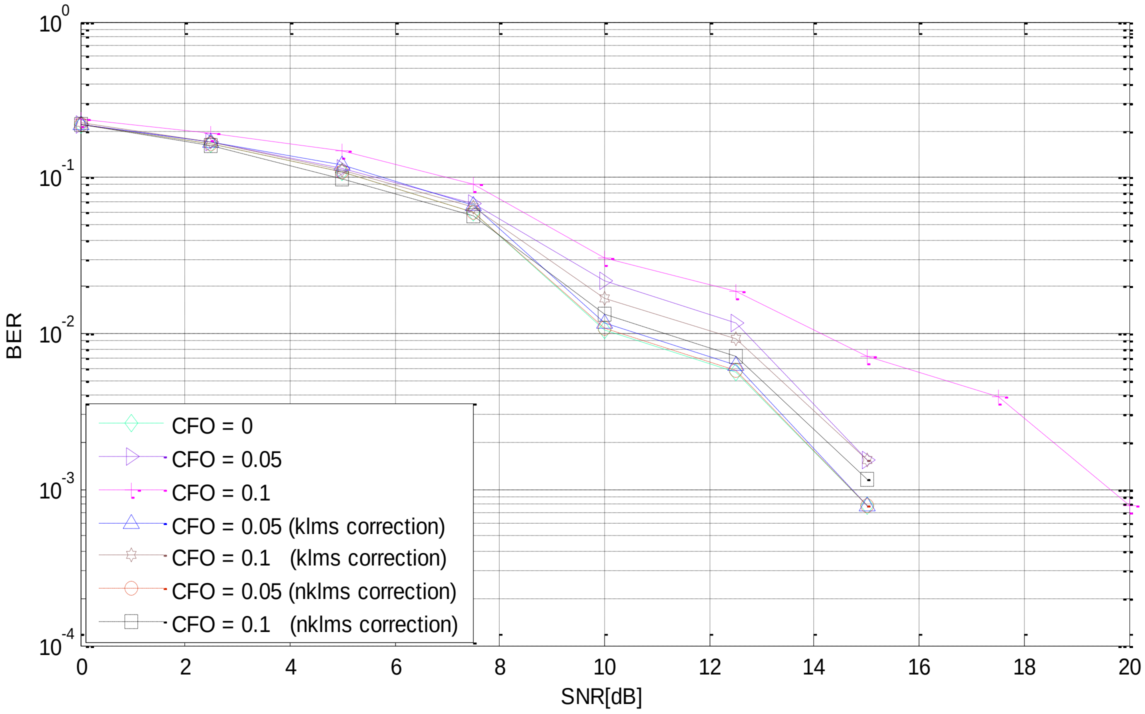

Fig. 4-4 Comparison of the KLMS and the NKLMS synchronization algorithms with carrier frequency offsets 0.05 and 0.1

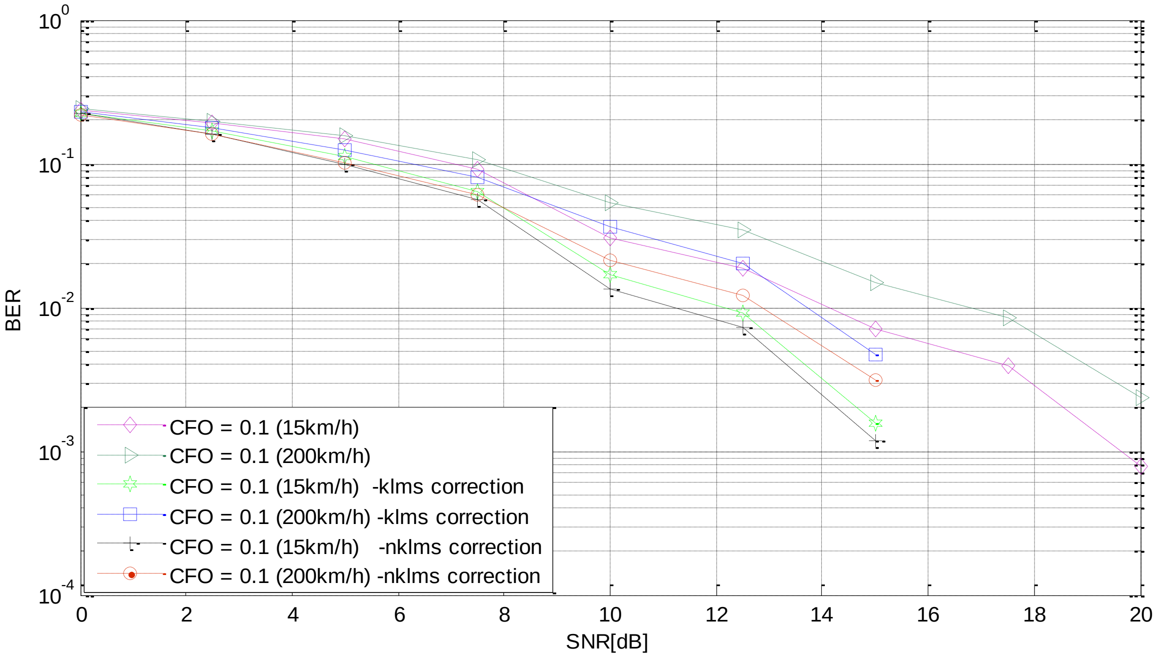

Fig. 4-5 Speed varying comparison of the KLMS synchronization algorithm with its normalized counterpart

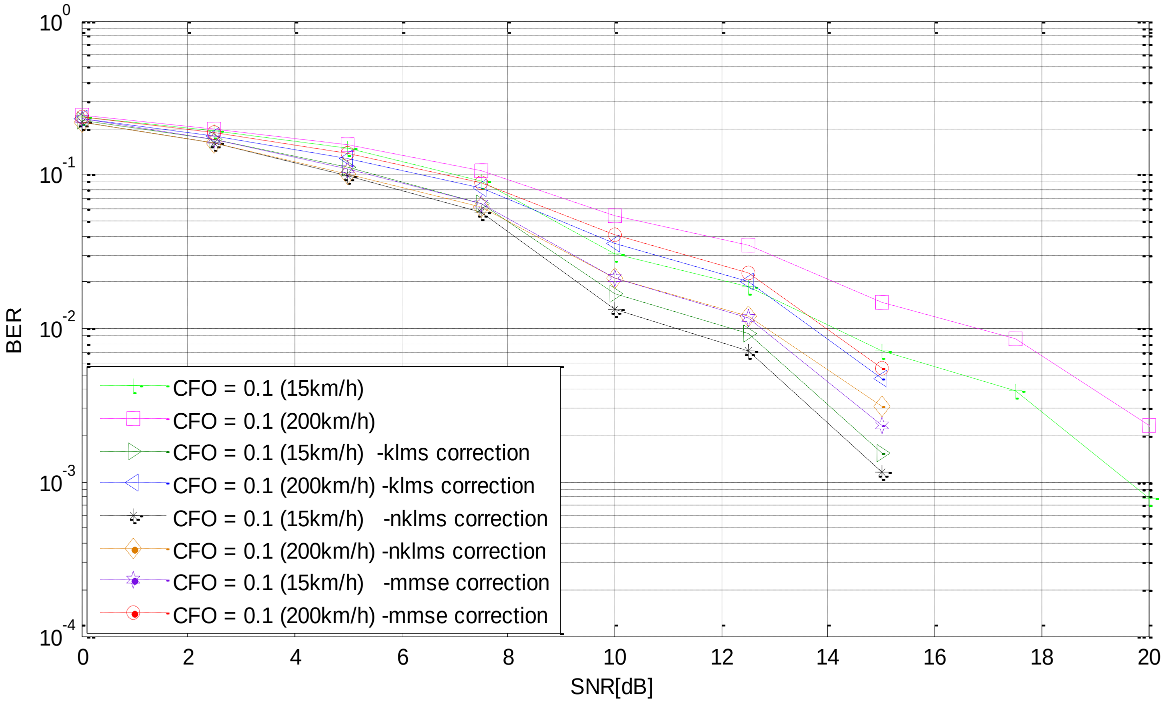

Fig. 4-6 BER performance of all the implemented synchronization algorithms in both slow and fast fading multipath scenario

4.4. Chapter Summary

In this chapter, two synchronization algorithms are proposed and implemented as improvements on the MMSE-based synchronization algorithm implemented in chapter 3. The KLMS algorithm and its normalized counterpart offer significant and more effective synchronization in the OFDM-IDMA system. These algorithms inherit the simplicity of the LMS algorithm and they are achieved by implementing the conventional LMS algorithm in the Kernel space. Simulation results are presented first to show the impact of the KLMS algorithm on the output of the multicarrier IDMA system. Then, to achieve a more stable and improved tracking, the NKLMS was implemented. Simulation results show that the NKLMS offers a better and effective synchronization process in the multicarrier system. Moreover, the KLMS algorithm and its normalized counterpart are compared with the MMSE-based synchronization algorithm as implemented in the previous chapter. The simulation results from the joint comparison, which have been documented, clearly show the respective influence of each of the algorithms on the overall performance of the OFDM-IDMA system. From the results, the MMSE algorithm offers the least bit error rate performance while the NKLMS achieved the most desirable and effective system output.

CHAPTER 5

CONCLUSION AND FUTURE WORK

5.1. Conclusion

A comprehensive research work has been carried out on the newly proposed OFDM-IDMA scheme. This noble scheme ensures an efficient utilization of the scarce spectrum as the demand for mobile communication increases. Wireless communication has recorded an extraordinary and exponential growth especially in recent decades. As a result, different schemes have been proposed in a bid to improve the overall efficiency of the cellular system. The various multiple access schemes used in the past generations were discussed in chapter 1, as well as the general peculiarity of the wireless channel.

In chapter 2, the multicarrier IDMA multiuser scheme and the major studies pertaining to this scheme was introduced and reviewed. The OFDM technique, which forms the bedrock of the hybrid OFDM-IDMA scheme, was discussed, pointing out the major challenges in this modulation technique. The concept of the multicarrier IDMA, as well as the ESE function, which carries out a coarse chip-by-chip detection to roughly remove interference among users in the system, were also examined and explained in detail. The design of the multicarrier IDMA system used is such that the cyclic prefix duration of the OFDM component is longer than the maximum channel delay spread of the multipath channel model. This effectively eliminates ISI as well as timing offsets in the system model. However, this scheme is susceptible to synchronization errors especially at the uplink due to the OFDM component present in the system. A thorough investigation and analysis was therefore carried out focusing on the more challenging impact of carrier frequency offset errors on the OFDM-IDMA scheme.

In chapter 3, the performance of the multicarrier system is investigated in a Rayleigh fading multipath channel, in the presence of CFO. Simulation results clearly show the degrading influence of CFOs, on the performance of the multicarrier system, adversely in contrast to early studies on this scheme [20, 55, 57], where the influence of CFOs on the overall system output was not considered.

Moreover, in chapter 3, in light of the degrading impact of synchronization errors on the performance of the OFDM-IDMA system, a linear MMSE-based synchronization algorithm is presented to combat this undesirable effect. The proposed algorithm focuses on the reduction of the ICI power due to the residual CFOs emanating from multiple simultaneous users in the system. From the equations derived, it was established that the presence of carrier frequency offset errors could be minimized by reducing the spectral power of the ICI. Simulation results show appreciable reduction and significant mitigation of carrier frequency offset errors upon the application of the MMSE-based algorithm. The overall bit error rate performance of the algorithm has been implemented and documented in a fast fading Rayleigh multipath channel with varying mobile speed.

In chapter 4, the KLMS algorithm was implemented for effective carrier frequency synchronization in OFDM-IDMA systems. The algorithm fundamentally involves the implementation of the LMS algorithm in the kernel space for effective prediction and correction. The KLMS algorithm, like the MMSE-based algorithm, was implemented in practical situations of high carrier frequency offsets with varying mobile speeds depicting both slow and fast fading multipath scenarios. Simulation results, which show the effectiveness and the significant influence of the KLMS algorithm has been documented. The ideal OFDM-IDMA scenario in which an error free system of CFO = 0 is assumed, is included in the implementation of the algorithms as a benchmark to clearly demonstrate the influence of the proposed algorithms no the multicarrier system model.

Finally, in chapter 4, the normalized counterpart of the KLMS algorithm called the NKLMS was implemented, to obtain a better system performance and stability. This algorithm excels in performance than the other implemented algorithms, as seen from the simulation results. The implemented algorithms were compared at different instances and a combined comparison was documented in fig. 4.6 where the BER performance of the implemented algorithms is presented concurrently. The application of the algorithms resulted in the significant improvement of the overall output of the multicarrier system. The algorithms also achieve great performances even in fast fading multipath scenario. However, it is noteworthy that the NKLMS algorithm offers a better, effective, and more efficient system performance than both its KLMS counterpart and the linear MMSE-based algorithm.

5.2. Future work

The focus of this research work has been on frequency synchronization in multicarrier IDMA systems. However, as the concept of OFDM-IDMA is relatively new, there is still much work to be done concerning this scheme. These other areas of possible research are listed as follow:

- First and foremost, practical issue such as the peak-to-average power ratio needs to be addressed in order to prevent non-linear distortions as well as reduction in the efficiency of the power amplifier in the system.
- Furthermore, as a multicarrier scheme, conspicuous power control techniques are essential for an effective interference management and efficient resource allocation.
- In this thesis, a perfect knowledge of the channel information is assumed, although this is not so in reality. There have been major studies in this regard but there is still much to be done to accomplish effective channel estimation with the lowest possible system complexity. Hence, more effective and less computational complex channel estimation techniques need to be developed for OFDM-IDMA systems.
- Moreover, for an improved system diversity and robustness, the multiple-input multiple-output (MIMO) technique, where multiple antennas are used at the transmitter and the receiver end of the multicarrier system, is another interesting area of research that needs to be investigated.

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