MULTICARRIER FREQUENCY HOPPING SPREAD SPECTRUM TECHNIQUES WITH QUASI-CYCLIC LOW DENSITY PARITY CHECK CODES CHANNEL CODING

ABID YAHYA

UNIVERSITI SAINS MALAYSIA

2010

MULTICARRIER FREQUENCY HOPPING SPREAD SPECTRUM TECHNIQUES WITH QUASI-CYCLIC LOW DENSITY PARITY CHECK CODES CHANNEL CODING

by

ABID YAHYA

**Thesis submitted to fulfillment the requirements
for the degree of
Doctor of Philosophy**

UNIVERSITI SAINS MALAYSIA

April 2010

ACKNOWLEDGMENTS

I would like to take this opportunity to express my deepest gratitude to all those people who have provided me with invaluable help over the course of my research.

I would like to acknowledge a tremendous dept of gratitude towards my Supervisor, Dr. Othman Sidek, whose patience, understanding, and guidance to me cannot be overstated. I thank to Dr. Othman Sidek for his directions and invaluable guidance in the research. His insightful directions and invaluable guidance provided during my research, not only complete my research also give me confidence. His financial support and advice during the conferences is unforgettable.

Next, I would like to express my gratitude to my Co- Supervisor, Dr. Mohd Fadzli Bin Mohd Salleh for his time, efforts, comments and valuable suggestions necessary to complete this work. I am extremely grateful for his labored efforts in proof reading this thesis.

I would like to express my sincere thanks to Prof. Farid Ghani for his guidance provided during writing Book Chapters.

Lastly, I owe a dept of gratitude to my family for their love, support, and sacrifice along the path of my academic purists. For all this and much more, I dedicate this thesis to them.

Thanks God for showing me the beginning and the end of a segment of the path of my life.

TABLE OF CONTENTS

CHAPTER THREE: METHODOLOGY

CHAPTER FOUR: RESULTS AND DISCUSSION

CHAPTER FIVE: CONCLUSIONS AND FUTURE WORK

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ACPR	Adjacent Channel Power Ratio
AWGN	Additive White Gaussian Noise
BCH	Bose-Chaudhuri-Hocquenghem
BER	Bit Error Rate
CCDF	Complementary Cumulative Distribution Function
CDF	Cumulative Distribution Function
CRC	Cyclic Redundancy Check
CSI	Channel State Information
dB	Decibels
DE	Density evolution
DSSS	Direct Sequence Spread Spectrum
FHSS	Frequency Hopping Spread Spectrum
FPGA Field	Programmable Gate Array
GSM	Global System for Mobile Communications
ISM	Industrial-Scientific-Medical
LUT	Look Up Table
MAP	Maximum Aposteriori Probability
MCFH-SS	Multicarrier Frequency Hopping Spread Spectrum
ML	Maximum Likelihood
OBW	Occupied Bandwidth
PN	Pseudo-Random (Spreading Code)
PSK	Phase Shift Keying

QC-LDPC	Quasi-Cyclic Low Density Parity Check
RSSI	Spectrogram and Received Signal Strength Indicator
SNR	Signal to Noise Ratio
VHDL	Very high speed integrated circuits Hardware Description Language

TEKNIK PEYERAKAN SPEKTRUM FREKUENSI PEMBAWA LOMPATAN PELBAGAI DENGAN PENYEMAKAN KOD SALURAN KUASI-BERKITAR BERKETUMPATAN RENDAH

ABSTRAK

Kerja ini membentangkan satu sistem baru Mengadapatasi Peyerakan Spektrum Frekuensi Pembawa Lompatan Pelbagai (MCFH-SS) menggunakan kod-kod Penyemakan Kod Saluran Kuasi-berkitar Berketumpatan Rendah (QC-LDPC) daripada menggunakan kod-kod kovensional LDPC. Satu teknik baru disarankan untuk membina kod-kod QC-LDPC berdasarkan kaedah pembahagian baris. Saranan kod-kod baru ini lebih fleksibel dalam ukur lilit, kadar-kadar kod dan panjang kod perkataan. Tambahan pula, satu skim baru juga disarankan untuk meramal saluran dalam sistem MCFH-SS. Teknik adaptif menganggarkan keadaan saluran dan menghapuskan keperluan sistem untuk menghantar satu pesanan permintaan pada awalnya sebelum menghantar paket data. Saluran sedia ada akan digunakan dengan satu kod Pseudonoise (PN) dan digunakan untuk penghantaran atau jika tidak, ia akan dihalang. Kod-kod QC-LDPC yang baru akan dibandingkan dengan kod-kod LDPC yang terkemuka. Prestasi Kadar Ralat Bit (BER) daripada kod-kod QC-LDPC yang dicadangkan dinilai dan dibandingkan ukuran blok daripada pendek ke panjang dengan kadar-kadar kod berbeza dan pecahan jalur lebar, ρ. Kod-kod QC-LDPC baru menunjukkan prestasi BER yang baik berbanding dengan kod-kod terkenal Mackay dan kod-kod PEG dengan bacaan E_b / N_o bernilai 0.15 dB dan 0.1 dB masing-masing pada 10^{-7} BER . Pelaksanaan perkakasan kod-kod QC-LDPC yang dicadangkan menggunakan papan pembangunan Xilinx Spartan-3E. Keputusan yang diperolehi daripada perkakasan untuk kod-kod QC-LDPC yang dicadangkan dengan senibina separa-selari adalah 111.6 Mbps.

Analisis perkakasan pelaksana kod-kod QC-LDPC mendedahkan yang kod-kod baru itu memerlukan sedikit ruang ingatan, oleh itu dapat mengurangkan kerumitan pada perkakasan. Kod-kod QC-LDPC yang disarankan telah digunakan dalam sistem adaptasi MCFH-SS sebagai kod-kod pembetulan kesalahan hadapan (FEC). Prestasi sistem adaptasi MCFH-SS pada kepelbagaian tahap 4, mengatasi sistem MCFH-SS

(tanpa skim saluran ramalan) dengan kelebihan 0.5 dB pada $\rho=1$ apabila kedua-dua sistem itu digabungkan dengan kod-kod QC-LDPC yang disarankan. Untuk E_b/J_0 bernilai 5 dB, sistem MCFH-SS dan sistem peyerakan frekuensi spectrum loncatan pantas (FFH-SS) mencapai BER 10^{-6} dan 10^{-4} masing-masing untuk 40 pengguna. Walaubagaimanapun, peningkatan prestasi ketara telah diperhatikan untuk jumlah pengguna yang sama (40) pada E_b/J_0 yang tinggi pada 50 dB di mana system MCFH-SS yang dicadangkan memperoleh nilai BER sebanyak 10^{-7} sementara system FFH-SS bernilai BER 10^{-3}. Hasil simulasi menunjukkan sistem adaptasi MCFH-SS yang disarankan mempunyai kelebihan berbanding sistem FFH-SS apabila sistem-sistem tersebut digunakan pada keaadaan yang sama. Keseluruhan sistem yang disarankan dilaksana pada platform perkakasan terdiri daripada kelengkapan pembangunan komunikasi yang menjadi antara muka dengan papan pembangunan Xilinx.

MULTICARRIER FREQUENCY HOPPING SPREAD SPECTRUM TECHNIQUES WITH QUASI-CYCLIC LOW DENSITY PARITY CHECK CODES CHANNEL CODING

ABSTRACT

This work presents a new proposed Multicarrier Frequency Hopping Spread Spectrum (MCFH-SS) system employing Quasi-Cyclic Low Density Parity Check (QC-LDPC) codes instead of the conventional LDPC codes. A new technique for constructing the QC-LDPC codes based on row division method is proposed. The new codes offer more flexibility in terms of high girth, multiple code rates and block length. Moreover, a new scheme for channel prediction in MCFH-SS system is proposed. The technique adaptively estimates the channel conditions and eliminates the need for the system to transmit a request message prior to transmitting the packet data. The ready-to-use channel will be occupied with a Pseudonoise (PN) code and use for transmission or else, it will be banned. The new QC-LDPC codes are compared with other well established LDPC codes. The Bit Error Rate (BER) performance of the proposed QC-LDPC codes is evaluated and compared for short to longer block lengths with different code rates and fractional bandwidth, ρ . The new QC-LDPC codes show good BER performance as compared to the renowned Mackay and PEG codes for given values of E_b / N_o by 0.15 dB and 0.1 dB at a BER of 10^{-7} respectively. The proposed QC-LDPC codes are implemented on FPGA chip using Xilinx Spartan-3E development board. The results obtained for the hardware implementation of the proposed QC-LDPC codes with partial-parallel architecture accomplishes a throughput of 111.6 Mbps.

Analysis of the hardware implemented QC-LDPC codes reveals that the new codes require less memory space, thus decreases the hardware complexity. The new QC-LDPC codes are employed in the proposed MCFH-SS system as forward error correction (FEC) codes. The performance of the proposed MCFH-SS system at diversity level 4, outperforms MCFH-SS system (without channel prediction scheme) with 0.5 dB gain at $\rho=1$, when both systems are coupled with the proposed QC-LDPC codes. It is shown from simulation results that for 40 users at E_b/J_0 of 5 dB, the proposed MCFH-SS system and fast frequency hopping spread spectrum (FFH-SS) system have BER of 10^{-6} and 10^{-4} respectively. The significant performance enhancement has been observed for the same number of users (40) at high E_b/J_0 of 50 dB that the proposed MCFH-SS system has BER of 10^{-7} while FFH-SS system with BER of 10^{-3}. Simulation results show that the proposed MCFH-SS system achieves considerable advantage over the FFH-SS system when the systems are used under similar conditions. The overall proposed system is implemented on a hardware platform comprised of a communication development kit that is interfaced with Xilinx development board.

CHAPTER ONE

INTRODUCTION

1.0. Preface

Consistent data communication on wireless channels is a very demanding task that implies different problems. The existing demand on higher consistency in mobile communications, the shortage of appropriate radio spectrum and the demand on higher data rates sets a lot of pressure on producing new techniques that can make use of the bandwidth much better.

Spread spectrum utilizes a novel shape of modulation in which the RF bandwidth of the signal is much larger than that demanded for conventional modulation methods. There are many spread spectrum (SS) techniques available, differing from each other on the type of modulation used such as the Direct Sequence (DS), Frequency Hopping (FH), Time Hopping (TH), Chirp, and hybrids methods (Cooper and McGillem, 1996; Dixon, 1994; Skar, 1988). Among those, the frequency hopping spread spectrum (FHSS) technique is chosen in this work due to its simplicity. The technique offers greater spreading even when a pseudo-noise (PN) sequence with small period is employed. Therefore, it allows a fast acquisition time in the receiver.

Recently there has been an increased in the interest in the development of FHSS system. This is due to the system has the ability to combat hostile interference. Frequency hopping is a technique where the carrier frequency is periodically changed during signal transmission (Muller, 2001). In frequency hopping technique a sequence of carrier frequencies is called the frequency hopping pattern. The set of M possible carrier frequencies is called the hopset. The rate at which the carrier frequency changes, is called the hop rate. Hopping occurs over a frequency band which is indicated as the hopping band. Each hopping band consists of many M frequency channels. Each frequency channel is defined as a spectral region that consists of a single carrier frequency as its center frequency of the hop set. The bandwidth B is large enough to include most of the power in a signal pulse with a specific carrier frequency.

Wireless communication systems have to be planned so that the required error protection levels are met. The construction of forward error correction (FEC) codes generally comprises of choosing a fixed code with a definite code rate, encoding/decoding complexity, and error-correcting capacity.

Channel coding is one of the major means that boost the transmission consistency at higher data rates. For practical applications in wireless communication systems, the channel coding scheme with low complexity and shorter length is preferred. In recent years have witness the more research efforts directing towards the discovery of lower complexity codes and iterative decoding. This proceeds to the rediscovery of Low

Density Parity Check (LDPC) code, which is originally proposed by Gallager in 1960 and afterward is extrapolated by MacKay (Mackay, 1999).

LDPC codes were neglected for a long time since their computational complexity for the hardware technology was high. LDPC codes have acquired considerable attention due to its near-capacity error execution and powerful channel coding technique with an adequately long codeword length (MacKay, 1999). LDPC codes have several advantages over Turbo codes. In the decoding of Turbo code it is difficult to apply parallelism due to the sequential nature of the decoding algorithm, while in LDPC decoding can be accomplished with a high degree of parallelism to attain a very high decoding throughput. LDPC codes do not need a long interleaver, which usually causes a large delay in turbo codes. LDPC codes can be constructed directly for a desired code rate. In case of turbo codes, which are based on Convolutional codes, require other methods such as puncturing to acquire the desired rate.

LDPC codes are in the category of linear codes. They cater near capacity performance on a large data transmission and storage channels. LDPC codes are rendered with probabilistic encoding and decoding algorithms. LDPC codes are designated by a parity check H matrix comprising largely 0's and has a low density of 1's. More precisely, LDPC codes have very few 1's in each row and column with large minimum distance. In specific, a (n, j, k) low-density code is a code of block length n and source block length k. The number of parity checks is delimitated as $m = n - k$. The parity check matrix weight (number of ones in each column or row) for LDPC codes can be either regular or irregular. LDPC can be regular if the number of ones is constant in each column or row and gets irregular with a variable number of ones in each column or row. A regular LDPC code is a linear block code whose parity-check matrix H constitutes exactly J 1's in each column and exactly $k = j\left(n/m\right)$ 1's in each row, with the code rate $R = 1 - j/k$.

There is a demand to design and develop LDPC codes over a wide range of rates and lengths with efficient performance and reduced hardware complexity. Properly-designed LDPC codes execute very close to the Shannon's theoretical limit and lower design complexity of the encoder and decoder. In view of this, LDPC codes are being projected as the channel coding solution for future modern digital communication systems.

1.1. Research Motivation

Transmission diversity enhances a communication system performance since it protects the system against jamming, multiple-access interference, and fading. In case of FHSS system, diversity is accomplished by incorporating the multicarrier to the system. Diversity is obtained by switching the transmit frequency more than once over one symbol duration. The transmit frequency is selected from the entire transmit frequency band.

1.1.1. Problem Statement

The use of fast frequency hopping (FFH) system may not be feasible for high data rate systems, due to its high speed requirements. Furthermore, in slow fading channels, performance of FFH system is less productive, since some of the subcarriers experiencing deep fading. Thus, degrades the system reliability. In order to achieve high rate and high quality transmission, an efficient frequency diversity and high bandwidth efficiency is required. This can be accomplished by the use of Multicarrier Frequency Hopping Spread Spectrum (MCFH-SS). The new system combined with channel coding and channel prediction scheme produces an adaptable, user-friendly and portable wireless system to characterize the RF spectrum over a wide range of frequencies.

There are many different methods to design the Quasi-Cyclic Low Density Parity Check (QC-LDPC) codes. Although these methods can be used to construct a wide range of codes, the capability is limited to generate codes with arbitrary girth, rate, and length. For practical applications, these methods are inappropriate to be used since they involve high encoding-decoding complexity.

The performance of the MCFH-SS system can be enhanced by incorporating the new proposed channel prediction scheme to the system. Usually, channels are banned only after it has been used to transmit data, which results in retransmission and loss of data.

In a severe condition, the system may end up employing the low quality channels regularly and would ban the good ones too frequently and disturbs the performance. Apparently, it is attractive to mitigate such undesirable consequences. However, in this research the system transmits short test packets on channels in order to predict the fit channels. If the test packet arrives is readable, the channel will be occupied with a Pseudonoise (PN) code and use for transmission or else, it will be banned.

1.1.2. Objectives

The key objectives of the work include:

I. To design QC-LDPC codes with reduced encoding and decoding complexity. The obtained codes should be flexible in terms of large girth, multiple code rates and large block lengths.

II. To design high throughput QC-LDPC codes with less hardware requirements.

III. To develop a new channel prediction scheme attempts to forecast and ignores the poor channels by transmitting short test packets on that particular channel uses the Pseudonoise (PN) codes.

IV. To develop a MCFH-SS system against external interference by incorporating with new channel prediction scheme together with channel coding based on new matric of diversity order.

1.2. Thesis Organization

The remainder of this thesis is organized in four main chapters: Chapter Two presents a review of frequency hopping spread spectrum, multicarrier frequency hopping spread spectrum, channel prediction scheme and low density parity check codes; in Chapter Three the methodology of the system is presented; in Chapter Four the results and performance analysis of the systems are presented; Chapter Five concludes the thesis.

Chapter Two surveys the literature as well as reference to some previous works in this particular field. It is divided into four main Sections, which discuss the work associated to frequency hopping spread spectrum, multicarrier frequency hopping spread spectrum, channel prediction scheme and low density parity check codes.

Chapter Three discusses the methodology of the system into five main Sections. Section 3.1 presents an overview of the renowned LDPC codes techniques and constructions. The design of new QC-LDPC codes is developed in Section 3.2. This section discusses the new codes in terms of girth, code rates and block lengths. Section 3.3 describes the design and development of the system employing MCFH-SS together with channel prediction scheme in order to set up the wireless modules, and to make them perform for communication. Section 3.4 describes the implementation of MCFH-SS protocols. This section discusses how the PN sequences are used to spread out frequency spectrum, reduce the power spectral density and minimize the jammer effects. While in Section 3.5, overall proposed system setup and hardware implementation is presented.

Chapter Four presents the comparison of the proposed QC-LDPC with other established LDPC codes, performance analysis of multicarrier frequency hopping spread spectrum system incorporated with proposed QC-LDPC codes, implementation of proposed QC-LDPC codes on FPGA board, spectrum analysis of the proposed system, interference analysis of the proposed system in Sections 4.1, 4.2, 4.3, 4.4 and 4.5 respectively.

Finally, Chapter Five puts forth the conclusions, presents a summary of the results and lays direction for future work in this area.

CHAPTER TWO
LITERATURE REVIEW

2.0. Introduction

A thought-provoking mission for wireless channels to communicate authentic data postulates many unusual problems. In wireless communication system, radio channels are commonly delineated as space, time and frequency deviating channel, dependent on the condition of signal to be transmitted (Durgin, 2002). A radio communication system should be designed in such a fashion that can bear the effects of fading of the signal. The multipath propagation of signal which turns out as Inter Symbol Interference (ISI) effects the incoming signal. Likewise, the wireless channel is incredibly noisy due to interference from other communication systems and the surroundings noise. In order to mitigate the effects of channel interference is to use error control coding. This chapter provides the literature survey related to this project as tabulated in Tables 2.1 to 2.10.

2.1. Frequency Hopping Spread Spectrum

The other method for converting the baseband data stream into larger bandwidth signal is using the FHSS technique. In FHSS technique the transmission bandwidth W Hertz is divided into q non-overlapping frequency slots. After the signal is modulated to an intermediate frequency, the carrier frequency is hopped periodically according to some pre-designated code (a pseudo-random sequence) (Don, 2005).

A patent Hedy Lamarr and music composer George Antheil (Don, 2005) for a "Secret Communication System," in 1942, is based on the frequency hopping concept, with the keys on a piano representing the different frequencies and frequency shifts used in music. In that year, the technology could not be realized for a practical implementation. Lemarr and Antheil incurred a patent for their idea soon after the expiry of the original patent. Then the U.S applied the FHSS technique for military communication systems onboard ships (Hoffman, 2002).

2.1.1. FFH/FSK System with Diversity Combining

It is well known that the low data rate signals are severely affected by the phase noise of microwave oscillator. The oscillator phase noise is usually treated as Gaussian distributed frequency noise, since its instantaneous frequency is simply the rate of change in phase. There have been many studies on phase noise of the frequency synthesizer over the past few decades as presented in (Barton and Norbury, 1986; 1988; 1989). Hussain and Barton (1993) examine the communication performance of a noncoherent FSK system with the phase noise of oscillator in the additive white Gaussian noise (AWGN) channel. In the proposed work the analysis is carried out based on the phase noise method. Teh et al. (1998) address the multitone jamming rejection of fast frequency hopping (FFH) / binary phase-shift keying (BFSK) linear-combining receiver over Rayleigh-fading channels. Shin and Lee (2001) analyze the performance of FFH system with diversity combining in Rayleigh, partial-band, and multitone jamming environments. The performance of an FFH/FSK system with diversity combining has been studied by Teh et al. (1998) and, Shin and Lee (2001) in detail. However, the effect of phase noise of frequency synthesizer to the system performance is not been considered in their study. Ryu et al. (2004) investigate the effect of phase noise on the FH frequency synthesizer on the performance of the FSK system. In the proposed work, the FH system with multihop per one symbol is considered. The in-phase, quadrature correlator, and square-law detectors are used for a noncoherent FSK demodulator. The linear diversity combining method is assumed for demodulation of the FFH system. SER of the system is derived by decision statistics method. It is observed from the results that the performance of FH system with respect to the relationship between phase noise and standard frequency deviation could be improved by estimating the optimum diversity level of the system.

Forward error correction codes provide an effective means of combating the effects of multiple-access interference (MAI) in frequency hopping spread spectrum-multiple access (FHSS-MA) networks. Kim and Cheun (2003) investigate various soft metrics to find those suitable for asynchronous fast frequency-hop spread-spectrum multiple-access (AFFHSS-MA) networks by employing binary Convolutional coding with orthogonal BFSK. Each frequency-hop slot in the proposed scheme is assumed to experience independent and flat Rayleigh fading. The work is focused on robust soft metrics computed from the outputs of the receiver matched-filters and with additional side information (SI) on the fading amplitude of the desired user. It is found from experimental results that appropriately chosen robust soft metrics offer performance far superior to the traditional metrics.

Li et al. (2004) introduce a kind of packet protocol for frequency-hopping multiple-access (FHMA) network based on the triple Data Encryption Standard (DES) block cipher frequency hopping sequences. In the proposed system each user possesses its FH sequence of frequency slots statistically independent with that of others and the mutual interference between transceivers has to be kept at as low a level as possible. In the proposed system, the logistic map function is adopted and the chaotic FH sequences generate in the network are of same size and satisfy Poisson distribution. The most key factor in the aforesaid work is the ratio of the packet length M to the frequency slots number q in order to determine the throughput and the normalized throughput of FHMA network. Simulation results demonstrate that 3-DES sequences produce significant performance as random hopping patterns, when used in FHMA systems.

Fuji-Hara et al. (2004) investigate frequency hopping multiple access (FHMA) systems by employing MFSK modulation scheme; with a single optimal frequency hopping sequence each from a combinatorial design-theoretic point of view. A correspondence between FH sequences and partition-type difference packings is established in order to acquire optimal FH sequences by constructing their corresponding difference packings of partition type. Optimal FH sequences are constructed, based on various combinatorial structures such as affine geometries, cyclic Steiner-designs, cyclically resolvable Steiner designs, and difference packings and families. The newly obtained optimal FH sequences are very useful in ultra wideband (UWB) communication systems (Scholtz, 1993). However, Authors emphasize on further research based on the generating methods and randomness properties of these, essentially the same FH sequences.

Su et al. (2001) derive the BER of the AFFH-MA system using multiple hops per symbol based on the maximum likelihood (ML) diversity combiner. The effectiveness of a two-stage multiuser detector is examined by authors, in which the first stage makes an initial decision while the second stage attempts to reduce MAI and settle the ambiguity left by the first stage detector. The MAI caused by undesired users is comprised by cochannel interference (CCI) contribution and an interchannel interference (ICI) contribution. This detector is of reserved complexity and is capable of removing most of the CCI and part of the ICI. Additionally, Joo et al. (2003) analyze BER of the synchronous FFH-MA system with a fixed timing offset. Although the proposed work is focused on the synchronous FFH-MA (SFFH-MA) system, but the work can be extended to the asynchronous case by replacing a fixed timing offset with a random delay and taking into consideration the MAI due to asynchronous transmissions of users in a precise way. Another simple method, using one-dimensional numerical integrations is introduced by Joo et al. (2005) for accurately evaluating the probability distribution for MAI and the BER of the AFFHMA system using multiple hops per symbol and the hard-limited linear (HL) combiner in Rayleigh fading. Based on numerical search algorithm, BERs of the proposed analysis and Gaussian Approximation (GA) method are obtained; results reveal that GA method also maintains a good accuracy for small SNRs/bit. However, the GA yields optimistic estimates as M and SNR/bit values increase.

FH based systems, such as Bluetooth radio systems are operating over the ISM band and are therefore, subject to PBNJ from external sources such as microwave ovens and lighting devices. Huo and Alouini (2001) present two approaches for the average BER evaluation of FFH/FSK systems with Product combining (PC) over Rayleigh channels subject to PBNJ. The proposed system has relied, first on the fact that the decision statistic at the output of PC receivers can be viewed as a product of F-variates to obtain the average BER in the form of a rapidly converging infinite series, for cases of practical interest. To present the second approach, the system is relied on the theory of function random variables for the average BER evaluation of PC over partial-band jammed Rayleigh-fading channels. Meijer's function for small values of the diversity order has been used in the proposed work and observes better performance of the system.

Ahmed et al. (2008) analyze the BER performance of the classic FFH-MFSK PC receiver by employing the Mellin Transform, when the transmitted signal is subjected to both Rayleigh fading and partial-band noise jamming. Authors derive probability density function (PDF) and CDF based on the Mellin transform technique for PC's output. It is shown in the proposed work that for FFH-MFSK system, PBNJ having a jamming duty factor of unity results in the worst-case jamming scenario communicating over Rayleigh-fading channels. Moreover, simulation analysis demonstrates that by increasing the modulation order or the diversity order, the BER performance of the system improves and if higher modulation order is employed, significantly greater diversity gain can be achieved from FFH. Authors emphasize on further research of the proposed system over Rician or Nakagami-*m* channels.

The linear diversity combining techniques with FSK modulation are presented for FFH system over Rayleigh-fading channels. Authors in the aforesaid not mention the highest level of the diversity order since the diversity order affects the hop of FFH system. And difficulties elevate in handling random delays of interferers, while investigating the performance of asynchronous fast frequency hopping multiple access systems. Furthermore, they used non-coherent modulation since difficult to maintain phase in FFH system but results with low throughput.

Table 2.1: FFH/FSK System with Diversity Combining

<table>
<tr><th>AUTHORS</th><th>YEARS</th><th>METHODLOGY</th></tr>
<tr><td>Ahmed et al.</td><td>2008</td><td>Derive probability density function (PDF) and CDF based on the Mellin transform technique for PC's output</td></tr>
<tr><td>Joo et al.</td><td>2005</td><td>Gaussian Approximation (GA) method with</td></tr>
<tr><td>Fuji-Hara et al.</td><td>2004</td><td>Optimal FH sequences are constructed, based on various combinatorial structures such as affine geometries, cyclic Steiner-designs, cyclically resolvable Steiner designs, and difference packings and families</td></tr>
<tr><td>Li et al.</td><td>2004</td><td>FHMA network based on the triple Data Encryption Standard (DES) block cipher frequency hopping sequences</td></tr>
<tr><td>Ryu et al.</td><td>2004</td><td>Linear diversity combining method</td></tr>
<tr><td>Huo and Alouini</td><td>2001</td><td>Product combining (PC) method over Rayleigh channels the hard-limited linear (HL) combiner in Rayleigh fading</td></tr>
<tr><td>Joo et al.</td><td>2003</td><td rowspan="2">Derive the BER of the AFFH-MA system using multiple hops per symbol based on the maximum likelihood (ML) diversity combiner</td></tr>
<tr><td>Su et al.</td><td>2001</td></tr>
<tr><td colspan="3"></td></tr>
<tr><th colspan="3">ANALYSIS</th></tr>
<tr><td colspan="3">The linear diversity combining techniques with FSK modulation are presented for FFH system over Rayleigh-fading channels. Authors in the aforesaid not mention the highest level of the diversity order since the diversity order affects the hop of FFH system. And difficulties elevate in handling random delays of interferers, while investigating the performance of asynchronous fast frequency hopping multiple access systems. Furthermore, they used non-coherent modulation since difficult to maintain phase in FFH system but results with low throughput.</td></tr>
</table>

2.1.2. Slow Frequency Hopping Spread Spectrum Communication Systems

The performance of slow frequency hopping spread spectrum (S-FHSS) communication systems subject to partial band interference and wideband noise is unacceptable without some form of retransmission scheme or error control coding. Elkashlan et al. (2006) present an efficient method to evaluate the performance of a channel-aware multiple-access scheme based on slow frequency hopping (CAFH) with r rounds in a slowly time-varying, frequency selective channel. Closed-form recursively-based expressions are derived in the proposed work to evaluate the BER, for CAFH with r rounds. BER curves of the proposed method are compared for the uplink of a system using CAFH with r=1 and 2, to that of conventional FH system by employing BPSK modulation with an average SNR of 2 dB. It is shown from the results that CAFH/BPSK can provide a much lower BER (at SNR of 2 dB can yield over a 100-fold reduction) than conventional FH/BPSK over a wide range of number of mobile stations.

Cabric et al. (2005) present a characterization of a real-time frequency-hopped, frequency shift-keyed testbed capable of transmitting data at 160 kb/s, with hopping rates of up to 80 Khops/s operating in the 900MHz band. The motivation behind the testbed is three-fold. First, to prove the feasibility of direct digital frequency synthesizer (DDFS) based on high-rate FH transmission, and investigates practical bounds on the achievable hopping rates. Second, to quantify the performance improvement achieves via equal gain hop combining for different hopping rates, and spacing between hopping channels, in terms of outage for a given Symbol-Error Probability (SER).

The hopping rate of the aforesaid system is slow in order to mitigate interference but on the other hand enhance the load on the system operation. Practical issues such as switching time and accomplishable hopping rates of a hopping synthesizer have been largely pushed aside. Moreover, most systems that have been realized in hardware do not fully exploit the advantages of frequency hopping, since they operate at slow hopping rates.

Table 2.2: Slow Frequency Hopping Spread Spectrum Communication Systems

<table>
<tr><th>AUTHORS</th><th>YEARS</th><th>METHODLOGY</th></tr>
<tr><td>Elkashlan et al.</td><td>2006</td><td>Closed-form recursively-based expressions are derived to evaluate the BER, for CAFH</td></tr>
<tr><td>Cabric et al.</td><td>2005</td><td>Prove the feasibility of direct digital frequency synthesizer (DDFS) based on high-rate FH transmission, and investigates practical bounds on the achievable hopping rates.
To quantify the performance improvement achieves via equal gain hop combining for different hopping rates, and spacing between hopping channels, in terms of outage for a given Symbol-Error Probability (SER).</td></tr>
<tr><td colspan="3"></td></tr>
<tr><th colspan="3">ANALYSIS</th></tr>
<tr><td colspan="3">The hopping rate of the aforesaid system is slow in order to mitigate interference but on the other hand enhance the load on the system operation. Practical issues such as switching time and accomplishable hopping rates of a hopping synthesizer have been largely pushed aside. Moreover, most systems that have been realized in hardware do not fully exploit the advantages of frequency hopping, since they operate at slow hopping rates.</td></tr>
</table>

2.1.3. Iterative Decoding of Frequency-Hopped Communication System

The problem of developing and utilizing side information in a frequency-hopped communication system is examined by Phoel (2005), by employing PSK modulation and contaminated by PBNJ. Estimating the unknown random carrier phase and detection of jamming signals are investigated in Phoel's work. A serially concatenated convolutional code structure with differential-ary PSK is employed as the inner code and an expanded trellis at the receiver end in the inner decoder to determine the phase ambiguity and is increased by a ratio-threshold test for detecting jammer energy. Simulation results present the performance of log- *a posteriori* probability (APP) and max-log-APP decoding algorithms, the comparison reveals that the performance of max-log-App is worst for large jammer fraction bandwidths; it actually performs better than the log-APP decoder at low values of fraction bandwidths.

Carrier phase continuity in frequency-hopped systems cannot be ensured at the boundaries of hops and, as a result, phase for each hop must be reacquired (Peleg and Shamai, 1997). Furthermore, in decoding jammed hops and their weight must be detected properly in order to combine information from different hops, optimally in a jamming environment. Peleg et al. (2000) approximate the continuously distributed random phase offset by a quantized phase. Authors use an expanded trellis in order to search over all possible sequences and the result is a mutual estimation of the data and the carrier phase. Other methods for conducting with unknown phase offset in an iterative fashion comprise of hard-decision feedback detection (Lampe and Schober, 2001), averaging over the uniform random phase in computing branch metrics in a trellis-based demodulator (Colavolpe et al., 2000; Peleg and Shamai, 1997), and iterative, explicit phase estimation (Hoeher and Lodge, 1999; Zhang and Burr, 2001; Anastasopoulos and Chugg, 2001; Nuriyev and Anastasopoulos, 2003; Lottici and Luise, 2004). It is observed that when the carrier phase is unknown but constant over the interval of ten symbols, the turbo coded system achieves BER lower than 10^{-3} at E_b / N_0 of 2.6 dB, which is 1.3 dB away from the capacity limit of this channel.

Kang and Teh (2003) extend the performance analysis of the coherent FFH system by employing binary phase shift-keying (BPSK) with the presence of PBNJ and AWGN to multiple hops per signaling interval. The bit error rate expressions for the coherent Maximum Likelihood (ML), Linear Combination (LC) and Hard Decision Majority Vote (HDMV) receivers in such systems are derived and validated by the simulation. Experimental results reveal that the coherent ML receiver offers the optimal performance and the coherent LC receiver is incapable of providing diversity improvement under the worst-case PBNJ condition. The performance of coherent HDMV receiver provides significant diversity improvement at moderate Signal-to-Jamming ratio (SJR).

Zhang and Tho (2002) investigate Turbo product codes (TPC) for use in FHSS communications in partial-band interference by employing binary orthogonal FSK with non-coherent envelope detection and perfect channel information. Instead of Chase algorithm, the proposed work has employed Fossorier-Lin algorithm of soft-decision decoding based on ordered statistics for soft-in/soft-out decoder to decrease the required E_b / N_J for a given packet failure probability. Simulation results show that for FHSS with memory, full interleaving is used in the proposed work for TPC to accomplish a good performance at low duty factors of partial-band interference. It is observed from the study that the TPC/FHSS is attractive for its low complexity and competitive performance.

A robust frequency-hopping system with non-coherent detection, iterative turbo decoding and demodulation, and channel estimation in (Torrieri, 2005 and Torrieri et al., 2008) in the environments including frequency-selective fading, partial-band interference, multitone jamming, and multiple-access interference. Spectrally compact non orthogonal continuous-phase frequency-shift keying (CPFSK) is introduced in the proposed work, which allows the optimal values of the modulation index, at a bandwidth constraint. A channel estimator based on the expectation maximization algorithm is derived in the proposed work, which accommodates both frequency-selective fading and interference. Experimental results reveal the excellent performance of the proposed system against both partial-band and multiple-access interference.

The performance of log- *a posteriori* probability (APP) and max-log-APP decoding algorithms is presented in above work, the comparison reveals that the performance of max-log-App is worst for large jammer fraction bandwidths; it actually performs better than the log-APP decoder at low values of fraction bandwidths. The employment of

Turbo codes in these decoder only decode the information these codes are unable detect the errors because based on Convolutional codes which required puncturing of columns for multiple rates. Moreover these systems require additional interleaver for processing. Decoder based on Log Likelihood Ratio (LLR), is required to overcome the shortcomings of the above work, since LLR based decoder reduces the bit error probability of the system.

Table 2.3: Iterative Decoding of Frequency-Hopped Communication System

<table>
<tr><th>AUTHORS</th><th>YEARS</th><th>METHODLOGY</th></tr>
<tr><td>Torrieri</td><td>2008, 2005</td><td>Iterative turbo compact non orthogonal continuous-phase frequency-shift keying (CPFSK)</td></tr>
<tr><td>Phoel</td><td>2005</td><td>a posteriori probability (APP) and max-log-APP decoding algorithms</td></tr>
<tr><td>Kang and Teh</td><td>2003</td><td>Maximum Likelihood (ML), Linear Combination (LC) and Hard Decision Majority Vote (HDMV) receivers</td></tr>
<tr><td>Zhang and Tho</td><td>2002</td><td>Fossorier-Lin algorithm of soft-decision decoding based on ordered statistics for soft-in/soft-out decoder</td></tr>
<tr><td>Peleg et al.</td><td>2000</td><td>Unknown phase offset in an iterative fashion comprise of hard-decision feedback detection using trellis-based demodulator</td></tr>
<tr><td colspan="3"></td></tr>
<tr><th colspan="3">ANALYSIS</th></tr>
<tr><td colspan="3">The performance of log- a posteriori probability (APP) and max-log-APP decoding algorithms is presented in above work, the comparison reveals that the performance of max-log-App is worst for large jammer fraction bandwidths; it actually performs better than the log-APP decoder at low values of fraction bandwidths. The employment of Turbo codes in these decoder only decode the information these codes are unable detect the errors because based on Convolutional codes which required puncturing of columns for multiple rates. Moreover these systems require additional interleaver for processing. Decoder based on Log Likelihood Ratio (LLR), is required to overcome the shortcomings of the above work, since LLR based decoder reduces the bit error probability of the system.</td></tr>
</table>

2.2. Multicarrier Frequency Hopping Spread Spectrum (MCFH-SS) Systems

Multicarrier frequency hopping spread spectrum (MCFH-SS) systems have received great attention because they take advantage of both multicarrier modulation and the FH concept and because they can be implemented coherently at the receiver when appropriately and specifically designed (Lance and Kaleh, 1997).

Chen et al. (1996) propose a modified multicarrier (MC) direct-sequence code division multiple-access (DS-CDMA) system with adaptive frequency hopping for use over slow multipath fading channels with frequency selectivity in the reverse link transmission of a cellular network. Rather than transmitting data substreams uniformly through subchannels, data substreams hop over subchannels with the hopping patterns adaptively adjusted to the channel fading characteristics. Authors design an efficient algorithm, based on the water-filling (WF) principle to determine the optimal hopping pattern and show that the performance, in terms of the average bit-error probability (BEP) is substantially better than that of single carrier RAKE receiver systems, conventional MC-CDMA systems applying moderate error protection, or diversity systems with different combining schemes. The proposed work illustrates that such an enhancement can be directly translated into an increase in CDMA system capacity. A similar, but more general, framework for applying the FH concept to multicarrier DS-CDMA schemes is proposed by Yang, and Hanzo (2001). Nonlinear constant-weight codes are introduced in the proposed scheme, in order to control the associated FH patterns and to competently share the system's frequency resources by each user. Furthermore, constant-weight codes are employed with different weights, in order to activate a number of subcarriers to support multirate services. Performance of the proposed system is evaluated by using a coherent RAKE receiver with maximum ratio combining (MRC) for demodulation and compare with that of corresponding single-carrier DS-CDMA and MC DS-CDMA systems, in a multipath Nakagami fading environment. It is observed from simulation results that the proposed SFH/MC DS-CDMA is competent of interworking with the existing 2G and 3G CDMA systems, while providing an evolutionary path for future unlicensed and broadband radio access networks (BRAN) without stiff and unnecessary spectrum fragmentation. Kim et al. (2005a) propose a truncated adaptive transmission scheme for the hybrid multicarrier CDMA/FDM system in forward link under single and multiple-cell environment. In the proposed scheme, a data substream is transmitted over the subchannels of which the channel gains are greater than a given threshold, based on the feedback information from the mobile station. The proposed scheme outperforms the adaptive FH/DS system as well as the conventional MC DS/CDMA system, in the single-cell environment, when orthogonal signature sequences are used. Authors emphasize on the orthogonality between users in order to eliminate the multiuser interference. It is found in the proposed scheme that by transmitting signals over good subchannels, the received signal energy is increased, while the interference from other cell base stations does not increase. The proposed scheme has better performance characteristics than the adaptive FH/DS system, in the multiple-cell environment when orthogonal or random codes are employed as spreading sequences.

A new allocation algorithm to overcome the limitations of WF algorithm in the MC-CDMA system with adaptive FH is proposed by Jia and Duel-Hallen (2006). In the proposed system signal to interference and noise ratio (SINR) is used instead of BER as the performance measure, and concentrate on the performance of the substream to maximize the SINR with the lowest SINR, since the error events are linked with that substream dominate the error rate. At the receiver end of MC-CDMA system, linear decorrelating detector is employed, in order to enhance the spectral efficiency. Authors investigate that the linear decorrelating detector that employs the proposed allocation algorithm is very effective in mitigating MAI, with performance approaching the single user bound for MC-CDMA system with adaptive FH.

Against the background of the extensive development of the Internet and the continued dramatic increase in demand for high-speed multimedia wireless services, there is an urgent requirement for flexible, bandwidth-efficient transceivers. Multi-standard operation is also an essential demand for the future generations of wireless systems. Yang and Hanzo (2002) demonstrate the possible implementation of the proposed FH/MC DS-CDMA scheme by software-defined radios, and its competence in handling multirate services. The FH/MC DS-CDMA exhibits a high grade of flexibility in the context of system design and parameter reconfiguration especially, in the existing second- and third-generation CDMA system bands (Yang and Hanzo, 2002).

Taking the advantage of a bandwidth-efficient multicarrier on-off keying (MC-OOK) modulation, Kim and Kim (2000) propose an efficient modulation method for frequency-hopped multiple-access (FHMA) communications in order to furnish a higher immunity against multiple-access interference in FHMA systems. Bit error probability of the proposed scheme is examined in slow frequency non-selective Rayleigh fading channels with background noise, while Sharma et al. (2007) analyze the same system but with FFH. The former system shows that MC-OOK/FHMA provides a lower interference over MFSK/FHMA for E_b / N_o greater than a threshold (interference-limited region), but the opposite is found to be true at low E_b / N_o . Experimental results indicate that the capacity gain that MC-OOK/FHMA system provides over MFSK/FHMA system in an interference-limited region is more than 2.5 dB, when the modulation alphabet size *M* is set to 8, and becomes higher for larger *M*. Wang and Huang (2002) propose a multicarrier direct sequence slow FH CDMA system with similar properties to that of conventional multicarrier DS-CDMA system, except that the main frequency subbands in the proposed scheme are divided into a number of hopping frequency dwells. A similar FH technique is applied by Elkashlan and Leung (2003) to a conventional multicarrier CDMA system, allowing for the narrowband frequency subcarriers of a user to hop within some groups of frequency slots. The proposed scheme is examined in an uncoded multi-access environment by utilizing a Gaussian assumption for the MAI.

Hong and Yang (2002) propose a multicarrier M-*ary* frequency shift keying (MFSK)/FH-CDMA, which utilizes FH patterns with cross correlation, not greater than