

A NOVEL BCS CODE IN F-OFDM SYSTEM: A PROMISING CANDIDATE
FOR 5G WIRELESS COMMUNICATION SYSTEMS

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To my beloved parents, thank you.



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ABSTRACT

Due to the rapid growth in wireless communication systems, Long Term Evolution (LTE), mainly based on Orthogonal Frequency Division Multiplexing (OFDM), no longer meets wireless communication systems request and higher data rate requirements. Thus, to support a number of users, higher throughput, reliability, and lower latency, 5G is a candidate to meet these features. Furthermore, OFDM does not meet the demand of 5G because of its high Out Of Band Emission (OOBE) and Peak to Average Power Ratio (PAPR). Filtered-OFDM (f-OFDM) is considered an alternative waveform for OFDM and a candidate technique for 5G because of its lower OOBE and similar features of familiar OFDM. However, there is a trade-off among reducing OOBE, Bit Error Rate (BER) degradation, and rising PAPR. Therefore, a novel BCS code has been proposed in this thesis for the filtered-OFDM system to improve BER performance with maintaining its low OOBE. It is created using a new methodology that differs from conventional concatenated RS/BCH codes. Hence, an inner RS (7, 1) code has been proposed to achieve compatibility with an outer BCH (15, 5) code and appended by interleaver to create a novel BCS code with low complexity. The results showed that using a novel BCS code in LTE system reduces BER, significantly improved to be better than single and concatenated RS/BCH codes with low decoding complexity. On the other hand, using a novel BCS code in f-OFDM system achieved 0.8dB coding gain at 8×10^{-3} BER and 1dB coding gain at 2×10^{-3} BER versus conventional OFDM system in both BPSK and QPSK modulation schemes, respectively. Meanwhile, the proposed system reduced both OOBE and PAPR lower than the conventional OFDM system. In conclusion, due to its low OOBE, improving BER, and minimizing PAPR better than conventional OFDM system, the proposed system is presented as a high competitor candidate of 5G wireless communication systems.

ABSTRAK

Oleh kerana pertumbuhan pesat dalam sistem komunikasi tanpa wayar, Evolusi Jangka Panjang (LTE), terutamanya berdasarkan Pemultipleksan Pembahagian Frekuensi Ortogonal (OFDM), tidak lagi memenuhi permintaan sistem komunikasi tanpa wayar dan keperluan kadar data yang lebih tinggi. Oleh itu, untuk menyokong sebilangan pengguna, pemprosesan yang lebih tinggi, kebolehpercayaan, dan latensi yang lebih rendah, 5G adalah calon yang mampu memenuhi ciri-ciri ini. Tambahan pula, OFDM tidak memenuhi permintaan 5G kerana Pelepasan di Luar Jalur (OOBE) dan Nisbah Kuasa Puncak hingga Purata (PAPR) yang tinggi. OFDM yang ditapis (f-OFDM) dianggap sebagai bentuk gelombang alternatif untuk OFDM dan calon teknik untuk 5G kerana OOBE yang lebih rendah dan ciri-ciri serupa OFDM yang biasa. Namun, terdapat pertukaran antara pengurangan OOBE, penurunan Kadar Kesilapan Bit (BER), dan kenaikan PAPR. Adalah perlu untuk menyeimbangkan isu-isu penting ini. Oleh itu, kod BCS baru telah dicadangkan dalam tesis ini untuk sistem OFDM yang ditapis untuk meningkatkan prestasi BER dengan mengekalkan OOBE yang rendah. Ia dibuat menggunakan metodologi baru yang berbeza dari kod gabungan RS/BCH konvensional. Oleh itu, kod RS (7, 1) dalaman telah dicadangkan untuk mencapai keserasian dengan kod BCH luar (15, 5) ditambahkan oleh antara lembara untuk membuat kod BCS baru dengan kerumitan rendah. Hasil kajian menunjukkan bahawa penggunaan kod BCS baru pada prestasi sistem LTE mengurangkan BER, yang mana secara signifikan meningkat menjadi lebih baik daripada kod RS/BCH tunggal dan gabungan dengan kerumitan penyahkodan yang rendah. Sebaliknya, menggunakan kod BCS baru dalam sistem f-OFDM mencapai keuntungan pengkodan 0.8dB pada 8×10^{-3} BER dan keuntungan pengkodan 1dB pada 2×10^{-3} BER berbanding sistem OFDM konvensional dalam skema modulasi BPSK dan QPSK. Sementara itu, sistem yang dicadangkan mengurangkan OOBE dan PAPR lebih rendah daripada sistem OFDM konvensional. Kesimpulannya, oleh kerana OOBE yang rendah, meningkatkan BER, dan meminimumkan PAPR lebih baik daripada sistem OFDM

konvensional, sistem yang dicadangkan dikemukakan sebagai calon pesaing tinggi sistem komunikasi tanpa wayar 5G.



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PERPUSTAKAAN TUNKU TUN AMINAH

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LIST OF ABBREVIATIONS

LTE	Long Term Evolution
QAM	Quadrature Amplitude Modulation
3GPP	Third Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
ARQ	Automatic Repeat Request
AWGN	Additive White Gaussian Noise
BCH	Bose–Chaudhuri–Hocquenghem
BCS	BCH+RS
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
CC	Convolutional Code
CDMA	Code Division Multiple Access
CP	Cyclic Prefix
CP-OFDM	Cyclic Prefix Orthogonal Frequency Division Multiplexing
DFT	Discrete Fourier Transform
ECC	Error Correction Code
E-UTRAN	Evolved UMTS Terrestrial Radio Access Network
FBMC	Filter Bank Multicarrier
FEC	Forward Error Correction
FER	Frame Error Rate
FIR	Finite Impulse Response
f-OFDM	Filtered Orthogonal Frequency Division Multiplexing
GF	Galois Fields
GFDM	Generalized Frequency Division Multiplexing

HD	Hard Decision
HST	High Speed Trains
ICI	Inter Channel Interference
ISI	Inter Symbol Interference
LDPC	Low-Density Parity-Check
LFSR	Linear-Feedback Shift Register
MCM	Multi Carrier Modulation
MIMO	Multi Input Multi Output
MIMO-SM	MIMO Spatial Multiplexing
MIMO-TD	MIMO-Transmit Diversity
ML	Maximum Likelihood
NR	New Radio
OFDM	Orthogonal Frequency Division Multiplexing
OBE	Out Of Band Emission
PAPR	Peak Average Power Ratio
QPSK	Quadrature Phase Shift Keying
RRC	Root-Raised-Cosine
RS	Reed Solomon
SCL	Successive Cancellation List
SCM	Single Carrier Modulation
SCMA	Spare Code Multiple Access
SD	Soft Decision
SFBC	Space Frequency Block Coding
SNR	Signal to Noise Ratio
TBCCs	Tail-Biting Convolutional Codes
TDD DL	Time Division Duplex Downlink
UFMC	Universal Filtered Multicarrier
UMTS	Universal Mobile Telecommunications System
VA	Viterbi Algorithm
W-OFDM	Windowing OFDM

LIST OF SYMBOLS

$\hat{P}_{PER}(f)$	Primitive polynomial
E_S	Energy per symbol
E_b	Energy per bit
H^T	Transpose of parity check matrix
N_0	Power spectral density
P_b	Bit probability of error
P_i	Primitive polynomial
P_r	Transmit power
R_b	Data bit rate
T_b	Bit time
T_g	Guard duration
T_s	Symbol duration
$W_R[n]$	Rectangular window
$W_{RRC}(n)$	Time response of RRC windowed filter
f_c	Carrier frequency
f_s	Sampling frequency
$g_k(t)$	The k th sub-carrier signal
x_n	Sampled signal
ω_c	Cut-off frequency of low pass filter
$\emptyset(X)$	Minimal Polynomial
$\emptyset(t)$	Graphically form of PSK signals
Δf	Frequency distance
$h(n)$	Time domain filter
A	Carrier amplitude
$C(X)$	Encoded data
$E\{.\}$	Mean value of the signal
H	Parity check matrix

M	Number of phases
$Q(z)$	Probability of a Gaussian random
$R(X)$	Parity check bits
SNR	Signal to noise ratio
$W(n)$	Time domain window function
$a(t)$	Bipolar data stream
$c(X)$	Code polynomials
d	Minimum distance
e	Smallest integer number
$e(X)$	Error polynomials
$erfc$	Complementary error function
$g(X)$	Generator Polynomials
k	Code dimension /BCH codes
	Number of encoded data symbols/ RS codes
m	Positive integer number
$m(X)$	Message polynomials
n	Block length/ BCH codes
	Number of code symbols/ RS codes
$n(t)$	Noise
q	A power of a prime number
$q(X)$	Quotient polynomials
$r(X)$	Received polynomials
$r(t)$	Received signal
s	Syndrome vector
$s(t)$	BPSK signal
t/BCH	Bits erroneous that can be corrected
t/RS	Symbols erroneous that can be corrected
α	Primitive element of $GF(2^4)$
β	Element
B	Bandwidth

CHAPTER 1

INTRODUCTION

1.1 Background

In modern societies, mobile communication has become one of the essential tools. The first generation has begun to move from connected fixed positions to personal communication. Quality of service and battery life of devices are increased depending on digital voice use in the second generation, expanding the system capacity. Furthermore, the introduction of the short message service in the second generation was considered a revolution in the method people communicate at that time. Mobile internet access and data rates have been enabled in the third generation. Thereafter, smartphones with high-definition cameras and screens as well as high processing capabilities with large storage led to higher throughput emerged in the fourth generation. Generally, mobile communication development starting from the second generation has been focused on increasing throughput [1]. Therefore, both industrial and academic fields focus on achieving the critical requirements in 5G cellular communications, such as very low latency, high throughput, ultra-spectral efficiency, and large number of connected devices [2]. In mobile communication systems, digital signals are generating errors due to fading and interference during the transmission. Different methods have been suggested to enhance the system's reliability and signal robustness, such as increase signal transmission power, error coding technology. However, channel coding techniques are still considered as common methods to minimize the system's error rate. The mobile communication network's 5G technology is regarded as a hot topic in the present mobile communication field. Using the channel coding technique is considered the foundation for achieving the 5G mobile communication system's reliability [3].

1.2 Problem Statements

Orthogonal Frequency Division Multiplexing (OFDM) is considered a key technology of broadband wireless communication systems including Long Term Evolution (LTE) [4,5]. It is suitable to resist the impact of multipath reception and thus enhance transmission efficiency as well as combats the Inter-Symbol-Interferences (ISI) [6-8]. Nevertheless, LTE does not meet the request of wireless communication systems and their higher data rate requirements because of the rapid growth in the service of these systems. In addition to high Out Of Band Emission (OOBE) and large Peak to Average Power Ratio (PAPR), it is supporting only one type of waveform parameter in the total bandwidth causing the OFDM system not to meet the demand of 5G diverse service scenarios. Therefore, Filtered-OFDM (f-OFDM) can promote a high data rate in 5G wireless communication systems, in addition to the features of OFDM, including a slight equalization complexity and flexibility of multiplexing and low OOBE [2,8]. Although f-OFDM system could achieve very low OOBE, unlike OFDM that suffers from high OOBE [8]. However, a trade-off exists between reducing OOBE and increasing both PAPR and Bit Error Rate (BER) [9], [10]. Thus, it is necessary to achieve balance among these three crucial issues.

On the other hand, several applications need a high transmission data rate, it requiring large bandwidth. It is difficult to increase the bandwidth due to the cost and spectral limitation. Hence, using the Multi Input Multi Output (MIMO) channel is a good solution for transmit diversity [11]. The MIMO technique is applied by using multi antennas in both of transmitter and receiver to exploit multipath fading to enhance data rates, channel capacity, network coverage, and link reliability [12]. Therefore, it has been proposed for 4G/5G in several researches [13-22]. MIMO technique has been used in LTE such as beamforming, transmit diversity, and spatial multiplexing, to achieve a higher peak rate with better system efficiency. It could improve cell coverage and achieve a higher data rate without increasing the frequency bandwidth or average transmit power [19].

In communication systems, channel coding techniques play a vital role after establishing Shannon's information theory [2]. Generally, modern radio communication requires a high data rate and low BER. In contrast, the transmitted data in wireless transmission channels are exposed to several factors (for instance,

multipath fading environments, atmospheric variations, and electromagnetic interferences). Due to these undesirable effects, the performance of any communication system will be unacceptable. Meanwhile, coding techniques are the only methods that can protect data transmission from errors. Using a suitable channel coding and modulation techniques could achieve the required BER and data rate [23]. Therefore, Error Correction Code (ECC) is considered one of the most important issues in digital communication systems via noisy channels to achieve the information transmission reliability [24]. Different Forward Error Correction (FEC) techniques have been suggested in 4G/LTE systems such as turbo code [25-32], convolutional code [33-35] and Low-Density parity-check (LDPC) code [36] to improve BER performance. On the other hand, channel coding techniques are indispensable for 5G mobile communication systems in achieving user requirements including latency, flexibility, complexity, and reliability [37]. Thus, to guarantee lower errors in the transmission message, all of turbo, LDPC, polar and convolutional codes have been suggested and compared for 5G mobile communication systems in [37-42].

1.3 Motivations

The following points are the motivations of this thesis:

1. To present an alternative waveform for OFDM systems suffering from high OOB and PAPR [8]. The filtered-OFDM system has been chosen as a strong candidate for 5G mobile communication systems, owing to its ability to overcome OFDM disadvantages and maintains its advantages [43].
2. To achieve the robustness in wireless communication systems' radio link, channel coding techniques are required [30]. So, a novel BCS code has been created in this thesis using a new methodology different from conventional concatenated RS/BCH codes, proposing it as a channel coding for the f-OFDM system.
3. To evaluate the proposed system's performance using a novel BCS code in both BPSK and QPSK modulation schemes. BCS code in the OFDM system has been used as a baseline for comparison purposes in BER performance, OOB, and PAPR.

4. To enhance data rates, channel capacity, network coverage, and link reliability, MIMO technique is applied to exploit multipath fading [12]. So, both (2×2) and (4×4) MIMO channels have been used in this thesis to improve link reliability of proposed system via multipath fading channel.

1.4 Objectives

This thesis's primary goal is to introduce a robust candidate waveform for 5G mobile communication systems. Hence, the objectives can be summarized as follows:

1. To investigate the proposed ECC's and MIMO systems in 4G/5G communication systems to improve their performance.
2. To identify a novel BCS code with high ability of error correction that outperforms single and concatenated (RS/BCH) code over multipath fading channel.
3. To achieve low decoding complexity in a novel BCS code by using an inner Hard Decision Decoding (HDD) RS code with an outer BCH code.
4. To develop a filtered-OFDM system through improving its BER performance, decreasing both OOB and PAPR by using a novel BCS code over the MIMO channel in the presence of a multipath fading channel.
5. To evaluate the performance of the proposed system by comparing it with the LTE system in terms of BER performance, OOB, and PAPR for both BPSK and QPSK modulation scheme.

1.5 Scope of the Thesis

The study in this thesis focuses on the following main components:

- Creating a novel BCS code with low complexity using an inner RS code with an outer BCH code then appended by interleaver. In this thesis, RS $(7,1)$ has been proposed to achieve compatibility with an outer BCH $(15, 5)$ code to create a novel BCS code.
- Using a novel BCS code in the f-OFDM system has been proposed and compared with conventional OFDM system over multipath fading channel

using (2×2) and (4×4) MIMO system for both BPSK and QPSK modulation schemes.

- Analyzing the parameters of BER, OOB, and PAPR in both systems f-OFDM and conventional OFDM to determine the waveform candidate for 5G mobile communication systems.

1.6 The Proposed Novelty of Research

In this thesis, a novel BCS code has been created using a new methodology of combining an outer BCH code with an inner RS code and appended by an interleaver. It is different from familiar concatenated RS/BCH codes which is created using an external RS code with an internal BCH code and separated by interleaver. To achieve the compatibility between both inner and outer codes, RS (7,1) has been proposed with an outer BCH (15, 5) code to create a novel BCS code. Owing to this new unique methodology, it outperforms both single (RS and BCH codes) and conventional concatenated RS/BCH codes. On the other hand, using MIMO in the proposed system contributes to further performance improvements by decreasing BER. Proposing a novel BCS code in the f-OFDM system could reduce both BER and PAPR with maintaining low OOB. Therefore, the proposed system may present as a contender waveform of 5G communication systems.

1.7 Thesis Organization

This thesis comprises five chapters, starting from the introduction in Chapter 1 explaining the background of mobile wireless communication systems and presenting the problem statements, motivations, objectives, scope of the thesis and the research proposed novelty. The rest of the chapters are introduced as follows:

Chapter 2 discusses the existing OFDM systems which is considered the 4G/LTE system's core waveform and presenting the advantages versus disadvantages. Moreover, the filtered-OFDM system which is regarded as highly contender candidate of 5G wireless mobile communication systems, is discussed in terms of its capability to solve the OFDM disadvantages while retaining its advantages. In contrast, MIMO systems proposed in 4G/5G communication systems have been discussed in this

chapter, along with the impact of using MIMO with 4G/5G systems. Lastly, channel coding techniques proposed in 4G/5G mobile communication systems have been presented and discussed both single and concatenated codes, as well as study the impact of using them in 4G/5G wireless mobile systems.

Chapter 3 explains the techniques and methods used in the proposed system. The system model and used parameters are also presented in this chapter. A novel BCS code has also been defined, and explaining the new methodology of combining RS and BCH codes that differs from conventional concatenated RS/BCH codes. The system performance evaluation has been lastly discussed in this chapter.

Chapter 4, shows the results and discussion of the proposed system presented and compared with conventional OFDM system. The comparisons have been made in terms of BER performance, OOB and PAPR values for both of BPSK and QPSK modulation schemes.

Chapter 5 shows the overall conclusions of the research. It presents the findings and discussions for both OFDM and f-OFDM systems. Future works have also been presented in this chapter.



CHAPTER 2

LITERATURE REVIEW

2.1 Background

One of the most objective standard of 4G mobile communication is providing high-speed data transmission, thus requiring extra cost and splitting technology standards that may decrease customers interest. Third Generation Partnership Project (3GPP) introduced the Evolved Universal Mobile Telecommunications System (UMTS) Terrestrial Radio Access Network (E-UTRAN), which is a standard of 4G mobile communication. It is different from the 3G standard, which utilizes Code Division Multiple Access (CDMA) schemes. LTE uplink transmission using Single Carrier-Frequency Division Multiple Access (SC-FDMA) while OFDM for downlink [44].

From the physical layer perspective, to support the requirements of 5G diverse efficiently and spectrum efficient network slicing, previous systems' fundamental challenges include LTE, that based on OFDM, the new design of waveform that allows the multi-service signal multiplexing and isolation. In addition to OFDM systems' features, e.g., simple implementation of channel estimation/equalization and multi-antenna technology, the new waveform should have two advantages to save the entire requirements of 5G; relaxed synchronization requirements and low OOB [45].

2.2 Systematic Review of 4G/5G Mobile Wireless Communication Systems

Figure 2.1 shows the taxonomy of the references in this thesis. Mobile communication systems started from the first generation (1G) which used Frequency Division Multiple Access (FDMA), followed by Time Division Multiple Access (TDMA) in the second generation (2G). Following from there, the CDMA was used in the third generation

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