UNIVERSITI TEKNOLOGI MARA

STBC MIMO FS-FBMC SYSTEM PERFORMANCE ENHANCEMENT USING AMM, JOS AND ECLS TECHNIQUES FOR 5G APPLICATION AND BEYOND

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PhD

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SITI MAISURAH BINTI SULONG

Thesis submitted in fulfilment
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ABSTRACT

As wireless technologies progress toward next-generation networks, the growing demand for higher data rates requires efficient communication systems, low power consumption, and robustness against channel impairments. Filter Bank Multicarrier (FBMC), first widely proposed in wireless communication research during the 4G era, remains a strong candidate for future multicarrier systems owing to its excellent spectral efficiency and absence of a cyclic prefix. Besides that, FBMC has gained attention as a promising multicarrier waveform due to its high spectral efficiency and strong resistance to carrier frequency offset. Despite these advantages, FBMC still faces several challenges, including high Peak-to-Average Power Ratio (PAPR), increased computational complexity, and intersymbol interference (ISI) under multipath propagation. To enhance FBMC performance, this research incorporates a Joint Optimization System (JOS) at the transmitter by combining clipping with μ-law companding, effectively lowering PAPR while preserving signal integrity. In the transmitter too, a simplified arithmetic technique known as the Additional Multiplication Method (AMM) is employed, utilizing only three addition and three multiplication operations to reduce computational complexity; the execution time of the algorithm is used as the primary measure of efficiency. Additionally, an adaptive Enhancement Cascaded Least Square (ECLS) algorithm sequence is applied into the receiver to mitigate ISI and improve symbol detection accuracy in multipath environments. Simulation results indicate that the combination of JOS, AMM and ECLS significantly strengthens the overall FBMC system. The proposed FBMC framework introduces an integrated approach that improves PAPR by 44.19%, reduces processing time by 10.49% and suppresses ISI by 93.10%. These improvements support the practical implementation of low-power and low-latency wireless systems for future 5G applications.

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TABLE OF CONTENTS

		Page
CONFIRMATION BY PANEL OF EXAMINERS		**ii**
AUTHOR'S DECLARATION		**iii**
ABSTRACT		**iv**
ACKNOWLEDGEMENT		**v**
TABLE OF CONTENTS		**vi**
LIST OF TABLES		**x**
LIST OF FIGURES		**xi**
LIST OF SYMBOLS		**xiii**
LIST OF ABBREVIATIONS		**xiv**
CHAPTER 1 : INTRODUCTION		**1**
1.1	Research Background	1
1.2	Problem Statement	5
1.3	Objectives	6
1.4	Scope and Limitations	6
1.5	Research Contribution	7
1.6	Thesis Organization	8
CHAPTER 2 : LITERATURE REVIEW		**9**
2.1	Introduction	9
2.2	Multiple Input Multiple Output	9
2.3	Orthogonal Frequency Division Multiplexing (OFDM)	12
2.4	Filter Bank Multicarrier (FBMC)	13
	2.4.1 Polyphase Network	15
	2.4.2 Frequency Spreading	17
	2.4.3 Offset Quadrature Amplitude Modulation (OQAM)	19
2.5	Performance of Peak Average Power Ratio (PAPR)	21
	2.5.1 Synchronization	22

2.5.2 PAPR Reduction Technique 24
2.6 Computational Complexity in Multicarrier Systems 32
2.6.1 Complex Multiplication Method 33
2.6.2 Karatsuba Method 34
2.6.3 Time Complexity Method 36
2.7 Intersymbol Interference (ISI) 38
2.8 Adaptive Algorithm 41
2.8.1 Least Mean Square (LMS) 43
2.8.2 Recursive Least Square (RLS) 51
2.9 Adaptive Equalizer 55
2.9.1 Linear Equalizer 56
2.9.2 Decision Feedback Equalizer 58
2.10 Diversity 60
2.10.1 Space Time Block Code 60
2.10.2 Space Frequency Block Code 62
2.10.3 Space Time Frequency Block Code 62
2.11 Summary 63

CHAPTER 3 : RESEARCH METHODOLOGY 64
3.1 Introduction 64
3.2 Research Flowchart 65
3.3 System Model 66
3.4 System Parameter 70
3.5 Simulation Flowchart 73
3.6 Additional Multiplication Method at the Transmitter 75
3.6.1 Block Diagram of AMM 76
3.6.2 Simulation Flowchart of AMM 78
3.7 Joint Optimization System at The Transmitter 82
3.7.1 Block Diagram of JOS with AMM 82
3.7.2 Simulation Flowchart of JOS with AMM 84
3.8 Enhancement Cascaded Least Square at the Receiver 88
3.8.1 Block Diagram of ECLS 89
3.8.2 Simulation Flowchart OF ECLS 90

3.9 Summary 94

CHAPTER 4 : RESULTS AND DISCUSSION 95

4.1 Introduction 95

4.2 Performance of JOS to Reduce PAPR 95

4.2.1 Comparison of PAPR Reduction Technique 96

4.2.2 Comparison Method Clipping Filtering (CF) And JOS 98

4.2.3 Comparison Of Different Type Of Multicarrier Modulation 100

4.2.4 Comparison Type Of FBMC 102

4.3 Performance of AMM To Reduce Complexity 103

4.3.1 Comparison Of BER Performance 103

4.3.2 Comparison Of Time Lapse 105

4.3.3 Comparison of PAPR Performance 106

4.4 Performance of AMM FS-FBMC to Reduce BER 108

4.4.1 Different Number of Antennas 109

4.4.2 Different Type Of Multicarrier Modulation 111

4.4.3 Different Number Of QAM Modulation 113

4.4.4 Different Type Of FBMC 115

4.4.5 Different Type Of Adaptive Algorithm 117

4.4.6 Computational Complexity Reduction Using RLS 119

4.5 Performance Of BER For 4x4 MIMO FS-FBMC 121

4.5.1 Diversity Technique 121

4.5.2 Comparison Type Of Equalizer 123

4.5.3 Comparison Type Adaptive Algorithm 125

4.6 Performance of JOS AMM ECLS MIMO FS-FBMC 127

4.6.1 Comparison of PAPR For AMM-JOS 127

4.6.2 Comparison Of BER For ECLS 130

4.6.3 Comparison Of BER Using Different Number Of Antenna 131

4.7 Summary 133

CHAPTER 5 : CONCLUSION AND FUTURE DEVELOPMENT 134

5.1 Conclusion 134

5.2 Future Development 135

REFERENCES **136**

AUTHOR'S PROFILE **155**

LIST OF TABLES

Tables	Title	Page
Table 2.1	Description for Equation (2.2)	15
Table 3.1	System Parameter Simulation[165]	70
Table 3.2	Coefficients of Prototype Filter	72
Table 4.1	Percentage Improvement PAPR Reduction Technique	97
Table 4.2	Percentage Improvement between CF and JOS	99
Table 4.3	Percentage Improvement of Multicarrier Modulation	101
Table 4.4	Percentage Improvement between PPN and FS	102
Table 4.5	Percentage Improvement Complex Multiplication Method	104
Table 4.6	Comparison of Complex Multiplication Method	106
Table 4.7	Percentage Improvement of Complex Multiplication Method	107
Table 4.8	Percentage Improvement Number of Antennas	109
Table 4.9	Performance Improvement of Multicarrier Modulation	111
Table 4.10	Percentage Improvement of Modulation Order	113
Table 4.11	Percentage Improvement Type of FBMC	115
Table 4.12	Percentage Improvement of LMS and RLS	118
Table 4.13	Percentage Improvement of RLS Performance	119
Table 4.14	Percentage Improvement of Diversity	122
Table 4.15	Percentage Improvement of Equalizer	123
Table 4.16	Percentage Improvement of Adaptive Algorithm	125
Table 4.17	Percentage Improvement of MIMO FS-FBMC	128
Table 4.18	Percentage Improvement of MIMO FS-FBMC	130
Table 4.19	Percentage Improvement of Different Number of Antenna	132

LIST OF FIGURES

Figures	Title	Page
Figure 2.1	MIMO Antenna Operations	10
Figure 2.2	FS-FBMC Transmitter	18
Figure 2.3	FS-FBMC Receiver	18
Figure 2.4	General Block Diagram For An Adaptive Filter With Algorithm	42
Figure 2.5	LMS Block Diagram	45
Figure 2.6	Linear Equalizer Process	57
Figure 2.7	Block Diagram Of The DFE	59
Figure 3.1	Methodology Of The Research Work	65
Figure 3.2	System Model Block Diagram (Overall)	66
Figure 3.3	Transmitter Section	67
Figure 3.4	Receiver Section	68
Figure 3.5	Simulation Process Of MIMO FS-FBMC	73
Figure 3.6	Complexity Reduction Techniques Using AMM	76
Figure 3.7	Simulation Flowchart of AMM For Complexity Reduction	78
Figure 3.8	Transmitter JOS For PAPR Reduction	82
Figure 3.9	Simulation Flowchart Of JOS Method For PAPR Reduction	84
Figure 3.10	ISI Reduction Technique Using ECLS	89
Figure 3.11	Simulation Flowchart of ECLS For ISI Reduction	90
Figure 4.1	Comparison Of PAPR Reduction Technique	96
Figure 4.2	Comparison of CF with JOS	98
Figure 4.3	Comparison of Multicarrier Modulation	100
Figure 4.4	Comparison Different Type Of FBMC	102
Figure 4.5	Comparison Of Complex Multiplication Method	104
Figure 4.6	Comparison Of PAPR Performance	107
Figure 4.7	Comparison Number Of Antennas For AMM	109
Figure 4.8	Comparison Different Multicarrier Modulation	111
Figure 4.9	Comparison Different Number Of QAM	113
Figure 4.10	Comparison Different Type Of FBMC	115
Figure 4.11	Comparison of Adaptive Algorithm For FBMC	117

Figure 4.12	Comparison of Reduction Complexity using RLS	119
Figure 4.13	Comparison of MIMO FS-FBMC with STBC	121
Figure 4.14	Comparison Of Different Type Of Equalizer	123
Figure 4.15	Comparison of Different Type Of Algorithm	125
Figure 4.16	PAPR Performance Of AMM JOS MIMO FS-FBMC	127
Figure 4.17	Comparison Of System Performance	130
Figure 4.18	Comparison Different Number of Antenna	132

LIST OF SYMBOLS

Symbols	
e	Error Signal
h	System Function
H	Channel Matrix
n	OQAM Time Slot
N	Number Of Subcarrier
m	Subcarrier Index
y	Receive Vector
λ	Forgetting Factor
μ	Step Size

LIST OF ABBREVIATIONS

Abbreviations

AWGN	Additive White Gaussian Noise
AMM	Addition Multiplication Method
BER	Bit Error Rate
ECLS	Enhancement Cascaded Least Square
CCDF	Complementary Cumulative Distribution Function
CP	Cyclic Prefix
DFE	Decision Feedback Equalizer
FBMC	Filter Bank Multicarrier
FFT	Fast Fourier Transform
FS	Frequency Spreading
IFFT	Inverse Fast Fourier Transform
ICI	Inter Carrier Interference
ISI	Inter Symbol Interference
JOS	Joint Optimization System
LE	Linear Equalizer
LMS	Least Mean Square
LTE	Long Term Evolution
MIMO	Multiple Input Multiple Output
MMSE	Minimum Mean Square Error
MSE	Mean Square Error
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OOB	Out of Band
OQAM	Offset Quadrature Amplitude Modulation
PF	Prototype Filter
PPN	Polyphase Network
PAPR	Peak Average Power Ratio
PTS	Partial Transmit Sequence
RLS	Recursive Least Square

SF	Space Frequency
SISO	Single Input Single Output
ST	Space Time
STF	Space Time Frequency
UFMC	Universal Filtered Multi Carrier
WMAN	Wireless Metropolitan Area Network
ZF	Zero Forcing

CHAPTER 1
INTRODUCTION

1.1 Research Background

In recent decades, wireless communication technology has delivered numerous benefits to society. Conventional wired system have mostly been replaced to enable wireless connectivity because of the overwhelming demands from users. Nowadays from 4G to the next G, this evolving technology rapidly grows and has exceptional ability to deliver efficient data transmission and connect people. [1]. One of the well known advanced wireless communication technology is the development of multipurpose antennas. This smart antenna capable of simultaneously transmitting and receiving multiple data streams. Researchers prove that the merging of enhancing technologies has amplified the overall impact on system performance. To utilize these benefits, this research applies Multiple Input Multiple Output (MIMO) smart antenna technology to enhance wireless system efficiency and reliability. MIMO is recognized as an advanced wireless communication technology because these multipurpose antennas enable simultaneous transmission of data signals across multiple dimensions including spatial (antenna), temporal, and frequency domains. This capability allows the system to deliver data streams simultaneously to different users hence improving overall network efficiency and reliability. The introduction of fifth-generation (5G) networks has driven communication systems to operate at mm-wave frequencies, where larger bandwidth resources are available [2].

To enhance system performance towards future networks, wireless technology introduces filter bank multicarrier (FBMC) as one of the potential candidates for data transmission [3]. Before, Orthogonal Frequency Division Multiplexing (OFDM) as a multiuser of digital modulation technique had been introduced as an implementation of the 4G and 5G physical layer [4][5] . During that period, networks employed OFDM to enhance wireless performance in environments affected by multipath propagation [6][7]. OFDM is different from FBMC with the direct implementation of the cyclic prefix (CP). However, OFDM suffers from poor frequency localization and exhibits a high Peak Average Power Ratio (PAPR), which are significant drawbacks [8][9]. OFDM heavily depends on the use of a cyclic prefix (CP) to minimize intersymbol

interference (ISI). This technique improves system performance but its also reduces spectral efficiency due to the additional overhead. Filter Bank Multicarrier (FBMC) has been introduced as a promising alternative to OFDM by offering superior spectral efficiency and robustness against carrier frequency offset. Furthermore, FBMC supports multiple simultaneous users by allocating distinct subcarriers within the radio frequency channel.

FBMC is considered attractive due to its ability to modulate subcarriers at twice symbol rate compared to OFDM [10]. These characteristics will enhance spectral efficiency and system performance. However, FBMC experiences intrinsic imaginary interference in the form of ISI because subcarriers of FBMC system maintain its orthogonality only in the real field. Referring to this research authors in [11], ISI will attenuate a signal waveform in the channel. The main role of equalizer at the receiver part is to reduce ISI and suppress noise for accurate signal recovery. In this research, different types of adaptive algorithms will be cascaded with Decision Feedback Equalizer (DFE) to effectively minimize ISI and enhance signal transmission. This non-linear equalizer provides better performance than linear equalizers because it avoids excessive noise enhancement and uses its feedback loop to cancel post-cursor ISI, resulting in more accurate symbol detection [12]. Although equalization greatly reduces interference, a certain level of residual ISI may persist due to the overlapping nature of the FBMC pulse shaping filters. Unlike OFDM, which employs a cyclic prefix to convert the channel into a circular convolution and simplify equalization, FBMC relies on well-designed prototype filters and per-subcarrier equalization techniques such as DFE to mitigate both ISI and intrinsic interference [13]. With appropriate filter design and properly configured DFE, the effective ISI can be significantly suppressed, enabling improved symbol recovery even in highly frequency-selective channels.

Although FBMC offers slightly better PAPR performance compared to conventional OFDM, the PAPR level remains high and needs to be addressed. A high PAPR reduces power efficiency because the power amplifier must operate with a larger back-off to prevent nonlinear distortion, resulting in lower usable output power and reduced transmission efficiency [14]. Simple PAPR reduction methods that are well known among researchers such as clipping, companding, filtering, selective mapping and partial transmit sequence have been explored in prior studies for both OFDM and FBMC systems [15] [16]. The proposed JOS integrates clipping with a companding approach to achieve better performance. Among various companding techniques

including hyperbolic tangent, error function, logarithmic, Mu-law, and A-law, the Mu-law method is selected in this research to complement clipping during the transmission process. Although various PAPR reduction techniques have been introduced, most existing studies focus on applying a single method which may introduce signal distortion and negatively affect BER performance.

Applying the basic reduction method of PAPR can cause degradation of BER and this problem has already been faced by many researchers [14][17][18][19]. To resolve the issue between PAPR and BER, this research utilizes an adaptive algorithm cascaded with an equalizer to enhance the performance of the system. As known by many researchers in wireless technology, adaptive algorithm is a procedure for adjusting the parameters of an equalizer or adaptive filter to minimize the cost function. A suitable filter structure together with an appropriate adaptive algorithm is essential for effective adaptive channel equalization, as both determine how accurately the equalizer can track channel variations and suppress distortion [20][21]. Least Mean Square (LMS) and Recursive Least Square (RLS) are two basic algorithms that have been used for a long time. This research develops an enhanced cascaded LMS–RLS algorithm structure by applying a training rate method to increase LMS convergence speed and a matrix-inversion technique to reduce the computational complexity of RLS. The basic LMS algorithm is widely used because it provides low computational complexity and stable performance. On the other hand, RLS is computationally more expensive because it requires recursive updates of the input correlation matrix at every iteration. However, this added complexity allows RLS to achieve a much faster convergence rate and better tracking ability than LMS [22][23]. While adaptive equalization techniques such as LMS and RLS have been investigated individually, the potential of cascading LMS and RLS to achieve better BER performance with reasonable complexity has not been sufficiently explored.

Recursive Least Squares (RLS) algorithm and conventional Filter Bank Multicarrier (FBMC) systems both suffers from computational complexity [24][25]. Frequency spreading (FS) technique and the polyphase network (PPN) structure have been recognized as a significant FBMC approach to overcome this challenge. These two techniques aim to balance system performance and complexity. Although the basic PPN method offers lower computational complexity, this research adopts the FS-FBMC approach instead because the frequency-spreading structure provides better control over subcarrier shaping, improved spectral localization, and enhanced robustness against

channel distortion compared to the traditional PPN method [26][27]. A new additional and multiplication method (AMM) is proposed to assist FS-FBMC to perform with lower complexity.

In wireless communication, improving reliability is always one of the main points. Space Time Frequency (STF) coding is widely used in OFDM systems to achieve this purpose. This method where information symbols are spread across antennas, time slots, and different subcarriers. Because of this, the system can take advantage of both spatial and frequency diversity, making it more resilient to fading. Because STF works well in OFDM, researchers have naturally started looking at how the same idea can be applied to FBMC, intending to enhance its diversity performance and boost overall signal robustness [28][29][30]. Space Time (ST) coding was one of the earliest techniques introduced to exploit the diversity offered by multiple antennas, providing gains through spatial and time diversity. However, the channel realization in slow-fading channels remains nearly constant across multiple time slots. It can limit the achievable time diversity and reduce the temporal diversity gain of space-time coding [31].

To address this limitation, Space Frequency (SF) coding was proposed. By spreading coded symbols across antennas and subcarriers instead of across time, SF coding is able to exploit both spatial and frequency diversity in multicarrier system [32]. Despite these improvements, earlier studies reported that neither ST nor SF coding is able to achieve full diversity in MIMO frequency-selective fading channels. Although both techniques can be adapted for multicarrier systems, their performance remains limited. This is because ST relies on OFDM to mitigate frequency selectivity and SF depending on the availability of resolvable multipath components. As a result, their performance is still not as strong as STF coding, which fully combines spatial, time, and frequency dimensions to provide maximum diversity [33][34]. Although SF, ST and STF approaches are well recognized in OFDM, these techniques in FBMC are still in their early stages.

1.2 Problem Statement

FBMC's achievement as one of the promising multicarrier modulation platforms for 5G systems has become an interesting topic among researchers. Although FBMC comes with many advantages but it still has its own limitations and weaknesses at the receiving end. High PAPR is the main drawback in all multicarrier systems as it distorts the signal which will lead to poor performance of BER and FBMC is not an exception [35]. Companding and non-companding techniques have been widely applied to reduce PAPR in multicarrier modulation systems. However, existing methods still has several limitations. The combination of selective mapping and partial transmit sequence introduces high computational complexity and may reduce the data rate while clipping can cause signal distortion despite achieving lowest PAPR value [15][36]. Therefore, existing techniques do not provide an acceptable balance between PAPR reduction, computational complexity, data-rate preservation and signal quality. This limitation creates a need for a more efficient PAPR reduction approach. To address this problem, the proposed JOS combines clipping and μ-law method to achieve improved PAPR performance with fewer drawbacks.

In addition to high PAPR, FBMC also faces high computational complexity. Frequency spreading is suitable for FBMC because it can be implemented directly by spreading the input data of each subchannel across several subcarriers [37]. However, existing multiplication approaches such as the basic matrix multiplication and Karatsuba methods require additional arithmetic operations thus resulting in longer processing time [38][39]. This limitation highlights the need for a more efficient multiplication method that can reduce the execution time of the FS-FBMC system. Therefore, the proposed AMM method is introduced into the frequency-spreading process to reduce processing time and improve the computational efficiency of the system.

Like OFDM, FBMC is also not immune to ISI that arises due to multipath propagation [40]. ISI is a distortion when a symbol interferes with the subsequent symbol and leads to noise during transmission. The communication will become less efficient if the previous symbol acts like noise. The digital data needs to be delivered to the receiver with the smallest error rate. Previously, OFDM systems rely on the use of a cyclic prefix (CP) to mitigate ISI and preserve orthogonality in multipath channels [41]. However, FBMC does not employ a CP due to its filter-based structure and offset-

QAM modulation. As a result, FBMC experiences different interference characteristics, especially in highly frequency-selective channels [42]. Due to this reason, DFE with cascaded least squares which is a hybrid of upgraded LMS and RLS will also be proposed in this research to combat the problem of ISI and at the same time apply ST to increase the diversity of the system. Based on these observations, there is a lack of studies that jointly address PAPR reduction, computational complexity reduction, and BER improvement in FBMC systems using practical and low-complexity implementation techniques.

1.3 Objectives

To address the limitations identified in the problem statement, this study outlines several research objectives aimed at analyzing and improving the performance of FBMC for wireless communications.

a) To design a MIMO FS-FBMC system for 5G networks using the JOS technique at the transmitter for PAPR minimization.

b) To develop an AMM algorithm at the transmitter for JOS-based MIMO FS-FBMC to reduce computational complexity while maintaining low PAPR.

c) To enhance the ECLS-DFE algorithm with STBC technique at the receiver by minimizing ISI for a lower value of BER.

1.4 Scope and Limitations

This research focuses on the simulation of a 4x4 MIMO antenna employing Frequency Spreading Filter Bank Multicarrier (FS-FBMC) techniques for 5G wireless communication. The study specifically examines the joint performance analysis of BER and PAPR in a MIMO FS-FBMC environment, an area that has not been extensively explored in existing literature. The proposed FS-FBMC framework is evaluated against alternative schemes such as a hybrid of clipping and μ-law and two joint adaptive algorithms. The system complexity was also analyzed using the proposed additional multiplication method. Decision Feedback Equalizer (DFE) and Space–Time (ST) diversity techniques were added to assess improvements in overall system performance. Simulation results are used to determine how equalization and diversity combinations

influence BER and PAPR behaviour. This study is limited to MATLAB-based simulations using a Rayleigh fading model with no hardware implementation. The analysis focuses solely on MIMO FS-FBMC configurations, and findings may vary when applied to other channel models, modulation schemes or antenna configurations beyond the scope of this work.

1.5 Research Contribution

This research delivers several technical contributions that enhance the performance of FBMC systems, particularly within 5G-oriented wireless communication. The work focuses on reducing PAPR, lowering computational complexity, minimizing BER and strengthening the reliability of FBMC-based MIMO transmission. The key contributions are summarised as follows.

i. Introduction of a distinctive MIMO FS-FBMC transceiver architecture that integrates AMM, JOS and enhanced cascaded LMS–RLS equalization to achieve simultaneous improvements in PAPR, computational efficiency and ISI mitigation.
ii. The introduction of a reduced-complexity complex multiplication scheme known as AMM using a 3 Multiplication with 3 Addition for FS-FBMC
iii. The integrated PAPR reduction framework for FS-FBMC using Combined Clipping and μ-Law Companding
iv. The implementation of cascaded adaptive equalization using upgraded LMS and RLS Algorithms for BER reduction.
v. The analysis of proposed techniques covers BER over Rayleigh Fading channel, PAPR distribution using CCDF and complexity evaluation

Overall, the core contribution of this research lies in the distinctive integration of JOS, AMM and ECLS equalization within a MIMO FS-FBMC framework to simultaneously reduce PAPR, shorten processing time and minimize ISI for lower BER. The research introduces robust performance and fills the gap in existing studies.

1.6 Thesis Organization

This thesis is organized into five chapters. Chapter 1 presents the introduction to the study, outlining the background of FBMC and FS-FBMC in 5G systems, the limitations of OFDM particularly with respect to CP usage, and the motivation for analysing joint BER and PAPR performance in a MIMO FS-FBMC environment. It also defines the research problem, objectives, scope, limitations, and contributions of the work.

Chapter 2 provides a comprehensive literature review covering OFDM, FBMC, and FS-FBMC signal structures and MIMO system fundamentals. It further discusses PAPR reduction methods such as clipping, filtering, and μ-law companding including the classical complex multiplication method. The chapter also reviews adaptive equalization techniques including LMS and RLS and highlights the motivation for adopting an upgraded cascaded LMS–RLS approach..

Chapter 3 describes the research methodology, detailing the overall system model for the MIMO FS-FBMC simulation conducted in MATLAB. It explains the implementation of the reduced-complexity multiplication method, the integration of PAPR reduction techniques including clipping and μ-law companding, and the design of the cascaded LMS–RLS equalizer.

Chapter 4 presents the simulation results and discusses the performance of the proposed MIMO FS-FBMC system in comparison with conventional methods. The findings include an analysis of BER improvements due to the upgraded LMS–RLS cascade, PAPR reduction achieved through clipping and companding schemes, and computational savings obtained with the reduced-complexity multiplication method, alongside comparisons with DFE and ST techniques.

Finally, Chapter 5 concludes the thesis by summarizing the main findings, emphasizing the contributions made to FS-FBMC system enhancement, and providing recommendations for future research.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

This chapter provides a comprehensive review of the fundamental concepts, techniques and system components relevant to this research including MIMO–Frequency Spreading FBMC (MIMO-FS-FBMC), Space–Time Block Coding (STBC), Joint Optimization System (JOS), Additional Multiplication Method (AMM), Enhancement Cascaded Least Square (ECLS) and equalization methods. This chapter also reviews the challenges related to inter-symbol interference (ISI), high PAPR and the computational complexity in multicarrier and MIMO systems. Previous works addressing these issues are analyzed to identify their advantages, limitations and areas where further improvements are needed. This chapter critically analyses previous studies and identifies the research gaps that motivate the proposed AMM-JOS-ECLS framework.

2.2 Multiple Input Multiple Output

Nowadays, multiple antenna technology has become the most promising technology to improve the range and performance of communication systems. Multiple antennas can be applied at the transmitter and receiver. This type of arrangement is called multiple input multiple output (MIMO) system. Based on this research, the authors [43] justified that the MIMO system has the capability to boost wireless systems in terms of capacity, data rate and coverage aspects. However, the transmitted signal will either takes other paths before reaching the receiver or bounce off objects considering it is impossible to avoid this type of problem. MIMO technology helps to attain high spectral efficiencies by sending different data streams on different transmit antennas simultaneously.

Authors in [44] also describe that an appropriate processing architecture will conduct these parallel streams of data. MIMO system is more complicated compared to a SISO but the signal is much better when using MIMO. These authors concluded that MIMO became more efficient due to the simultaneous transmission of the signal from

different antennas. This type of smart antenna has been successfully proven in IEEE 802.11[45]. MIMO with OFDM and FBMC have also been studied by authors in [46][47]. The authors proved that MIMO combined with FBMC achieves better performance compared to MIMO-OFDM because of the presence of well-designed prototype digital filters in FBMC that provide superior spectral containment and reduced out-of-band emissions. This filtering capability enhances robustness against interference and improves spectral efficiency. Furthermore, the authors emphasized that the number of antennas significantly influences system performance where increasing the antenna configuration enhances spatial diversity and improves system reliability. However, despite these advantages research on MIMO-FBMC remains relatively limited compared to the extensive studies available for MIMO-OFDM particularly lack of comprehensive studies addressing practical implementation challenges.

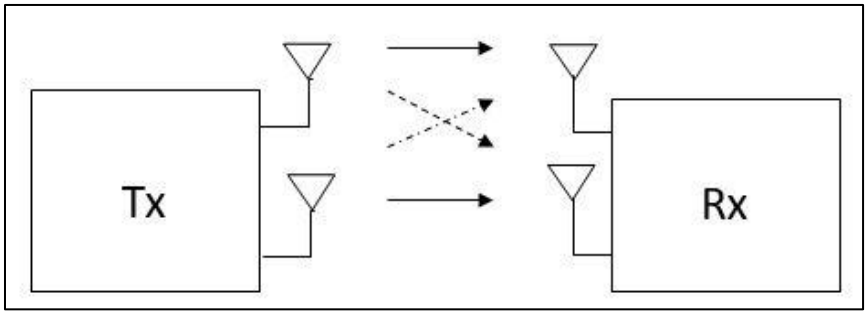

Figure 2.1 MIMO Antenna Operations

Based on the Figure 2.1 above, the MIMO antenna system operates by using multiple antennas at both the transmitter and receiver. Each receive antenna collects signals transmitted from both antennas at the transmitter, since wireless signals propagate through multiple spatial paths. In a 2×2 MIMO setup, the symbols are arranged in pairs and transmitted simultaneously from the two transmit antennas within each time slot. This allows more information to be sent at the same time, which effectively increases the data rate because the system uses the time slot more efficiently compared to SISO. Although MIMO provides stronger signal quality and higher throughput, the overall system becomes more complex due to the requirement for multi-antenna processing and accurate channel estimation.

The efficiency of a MIMO system can be maximized by enabling the simultaneous transmission of signals from multiple antennas as stated by the authors [44][48] hence exploiting spatial multiplexing and diversity gains to enhance system

capacity and reliability. Besides that, increasing the number of antennas at the receiver allows it to capture multiple copies of the transmitted signal thereby enhancing spatial diversity and achieving a higher diversity order [49]. To design an efficient MIMO system, several critical propagation factors must be carefully considered. Free-space and path loss play a fundamental role in determining signal attenuation over distance which directly affects coverage and received signal strength. In addition, environmental obstructions such as trees, rocks, and mountainous terrain introduce shadowing effects that further degrade signal quality. In urban environments, dense infrastructure and buildings contribute significantly to multipath propagation causing reflections, scattering, and potential inter-symbol interference. User mobility introduces additional impairments including Doppler shift and delay spread particularly in dynamic channels which can severely impact system reliability and overall performance.

Finding	Limitation	Reference
The modified variable-step-size leaky LMS improves channel estimation and convergence in noisy conditions.	It was tested mainly for OFDM and has higher complexity than conventional LMS.	44
OFDMA improves spectrum sharing and supports multiple users in WiMAX and LTE.	It does not study BER, PAPR, FBMC or adaptive equalization in detail.	45
Diversity combining improves the BER performance of MIMO-FBMC over AWGN and Rayleigh channels.	It only considers basic channel models and does not study PAPR or computational complexity.	46
The single-tap equalizer reduces receiver complexity in MIMO-FBMC under doubly selective channels.	Its performance may decrease in severe frequency-selective channels	47
Load-based resource sharing improves throughput and resource allocation in 5G MIMO systems.	It focuses on network resources rather than PAPR, ISI or FBMC equalization	48
MIMO-OFDM with space-time coding improves BER and system reliability.	It still suffers from high PAPR and cyclic-prefix overhead.	49

2.3 Orthogonal Frequency Division Multiplexing (OFDM)

OFDM is a widely adopted multicarrier modulation technique in modern wireless communication systems. It divides a high-rate data stream into multiple lower-rate streams transmitted simultaneously over orthogonal subcarriers. The available bandwidth is partitioned into these subcarriers, which are transmitted in parallel to improve spectral efficiency. In order to preserve orthogonality and mitigate intersymbol interference (ISI) caused by multipath propagation, OFDM employs a cyclic prefix (CP). The CP acts as a guard interval, converting the channel's linear convolution into circular convolution, thereby simplifying equalization. Despite these advantages, OFDM performance can still be affected by multipath fading and Doppler shifts in dynamic environments.

These multipath effects cause signals to arrive at the receiver from different directions, potentially introducing distortion. In modern urban environments, wireless signals often experience reflections and scattering from obstacles such as buildings, vehicles, and trees. OFDM addresses these challenges by achieving high spectral efficiency through closely spaced subcarriers and maintaining data integrity with relatively low symbol rates. Fundamentally, OFDM operates by dividing a high-rate data stream into multiple parallel subcarriers using frequency division multiplexing.

In addition, previous researchers have stated that each sub-carrier in an OFDM system must lie at the zero-crossing points of all other sub-carriers. Consequently, sub-carrier spacing must be carefully selected because, although the spectrum of adjacent sub-carriers overlaps, they will not interfere with each other as long as they are sampled at the correct sub-carrier frequencies [50]. Recent research continues to support this classical principle, emphasizing that orthogonality is highly sensitive to any disturbance in the expected zero-crossing alignment. The authors study on OFDM transmission in challenging propagation mediums, where severe channel dispersion and attenuation further amplify the importance of accurate sub-carrier spacing. The study proposes adaptive signal design to preserve orthogonality in non-ideal environments. These findings reinforce that maintaining precise sub-carrier spacing and ensuring correct zero-crossing alignment remain fundamental to achieving reliable OFDM performance [51]. OFDM signal can be expressed as in the equation below [52];

$$v(t) = \sum_{k=0}^{N-1} X_k e^{\frac{j2\mu kt}{T}}, 0 \leq t < T \quad (2.1)$$

Based on the equation (2.1) X_k is the complex symbol of subcarrier k, N is the number of subcarriers and T is OFDM symbol time. The subcarriers were orthogonal if they did not interfere with each other. Although OFDM has become a widely adopted multicarrier modulation technique due to its simple implementation, OFDM still faces several limitations, particularly its reliance on the CP to combat ISI.

These limitations of OFDM especially the use of a cyclic prefix, high out-of-band emissions and lower spectral efficiency led to the development of FBMC as a more efficient alternative waveform.

Finding	Limitation	Reference
OFDM provides high spectral efficiency and reduces multipath interference using orthogonal subcarriers.	It suffers from high PAPR and is sensitive to frequency offset	50
OFDM improves deep-sea communication capacity by approximately 2.5 bps/Hz over long distances	The study focuses only on underwater electric-current channels and conventional OFDM	51

2.4 Filter Bank Multicarrier (FBMC)

FBMC is another approach by researchers to achieve lower latency during 5G evolution that cannot be accomplished by 4G technologies [1][53]. The most challenge in wireless communication nowadays is the demand for multimedia services that can be accessed by many simultaneous users with less complexity, interference and power usage. OFDM gains interest for the last few years and had been proposed for the 4G network. OFDMA is also attracting the researcher's attention as a promising next generation broadband wireless network. This multiple access technique is based on the flexibility of time and frequency domain resources.

However, as the years passed by, next-generation mobile networks demanded more data with optimal use of spectrum. FBMC is among the promising methods of multicarrier transmission for the 5G network. Authors in [54] were comparing OFDM and conventional FBMC as a 5G multiplexing technique. It was proven that FBMC as a dominant waveform contender was an effective solution for OFDM in terms of power

spectral densities, complexity and subchannels. The authors conclude that there is still room for improvement for FBMC to have better performance in the wireless communication system. Authors in [8] also compare waveform candidates for 5G that fulfill key performance indicators (KPI). OFDM which is extensively used by Long Term Evaluation (LTE) and Long Term Evaluation Advanced (LTE-A) before actually experienced many problems for example, high spectral leakage, high out-of-band emission, high PAPR and high bit error rate (BER) when using high modulation schemes compare to FBMC. However, the performance of FBMC still need to be enhanced in terms of PAPR and complexity.

FBMC outperformed OFDM in terms of BER and PAPR also stated by authors in [3]. The authors also compare FBMC with filtered OFDM (F-OFDM). The result shows that F-OFDM is more compatible with MIMO compared to FBMC because the modulation technique can be directly applied and maintain its orthogonality. Interference from not including CP during transmission makes FBMC less compatible to MIMO. However, F-OFDM suffers from high complexity and loss of spectral efficiency because of the direct implementation of CP. Although FBMC might perform much better with the presence of CP by referring back to the performance of OFDM with CP, still no researchers are focusing on the application of CP in FBMC compared to OFDM because CP cannot be directly tested to FBMC resulting in high complexity during channel equalization [55]. The basic FBMC equation can be addressed as below [26] ;

$$x(t) = \sum_{k=0}^{K-1} \sum_{m=-\infty}^{\infty} [a_k(m)h(t-mT) + jb_k(m)h\left(t - mT - \frac{T}{2}\right)] e^{jk\varphi_t} \tag{2.2}$$

$$\varphi_t = \frac{2\pi t}{T} + \frac{\pi}{2} \tag{2.3}$$

With (2.3) as a simplified subcarrier phase term.

Table 2.1
Description for Equation (2.2)

$a_k(m)$	real part of *m*th symbol
$b_k(m)$	imaginary part of *m*th symbol
K	number of subcarrier modulators
T	symbol period
h(t)	Impulse response of the filter

Suitability of FBMC as a physical layer waveform for next-generation wireless communication systems has also been mentioned by authors in [56]. The authors evaluate FBMC performance in terms of spectral efficiency, BER and power spectral density, and compare it with conventional OFDM. Their results show that FBMC offers significantly reduced out-of-band emissions and improved spectral containment without presence of cyclic prefix. This makes it more resilient to spectral leakage. The study concludes that FBMC is a strong candidate for future wireless systems, particularly in scenarios requiring high spectral efficiency and efficient spectrum utilization.

Finding	Limitation	Reference
FBMC provides better spectral efficiency and lower out-of-band emission than OFDM.	It has higher implementation complexity and challenging MIMO integration.	3
FBMC and other 5G waveforms can improve energy efficiency and spectrum coexistence.	The study is mainly a review and provides limited simulation validation.	8
FBMC performs better than OFDM in spectral efficiency, BER and out-of-band radiation.	FBMC requires more complex filtering and signal processing.	54
FBMC improves spectral containment and reduces interference compared with OFDM.	The study has limited channel scenarios and does not investigate advanced equalization or PAPR reduction.	56

2.4.1 Polyphase Network

Polyphase network (PPN) structures are essential for the practical deployment of Filter Bank MultiCarrier (FBMC) systems, as they significantly reduce computational complexity. In FBMC, each subcarrier is shaped using a well-localized prototype filter to ensure low out-of-band emissions and high spectral efficiency. However, directly

applying these long prototype filters with multicarrier signals results in significant cost. Researchers introduced a polyphase network to address this challenge, which breaks down the prototype filter into multiple subfilters operating at lower sampling rates. This approach enables efficient integration of filtering with FFT/IFFT operations, making FBMC suitable for real-time applications.

Authors in [57] proposes a short-length prototype filter to reduce latency and computational complexity in FBMC/OQAM systems. Unlike conventional long filters, the proposed design minimizes symbol overlapping while preserving real-domain orthogonality. Simulation results show that the filter achieves BER performance comparable to traditional FBMC filters with only minor degradation in spectral confinement, which remains superior to CP-OFDM. The findings also indicate that the FS-FBMC receiver achieves lower hardware complexity than the PPN-FBMC receiver with the proposed method.

Extensive research has been done to analyze more about PPN and FS. Husam and Zsolt propose a Hopping Discrete Fourier Transform (H-DFT) technique that selectively processes only the active subcarriers instead of performing full-size FFT operations [58]. The authors grouped transceiver FBMC into two approaches, which are PPN and FS design. The PPN-based design offers lower computational complexity while the FS-based architecture provides superior performance at the receiver. This approach significantly reduces the number of required multiplications and memory accesses while preserving the accuracy of conventional FS-FBMC receivers. Simulation and complexity analyses show that the proposed H-DFT–based receiver achieves comparable performance to standard FS-FBMC implementations with noticeably lower hardware complexity, making it well suited for practical and resource-constrained wireless receiver designs.

Recent research by authors in [59] proposes an enhanced QAM-FBMC system implemented using a PPN architecture. Unlike conventional OQAM-FBMC, the proposed scheme enables the direct use of QAM symbols by employing jointly optimized mismatched prototype filters at the transmitter and receiver. This design effectively suppresses intrinsic interference, allowing complex-domain orthogonality while maintaining the low out-of-band emission. Simulation results demonstrate that the proposed PPN-based QAM-FBMC system achieves better performance of BER compared to traditional FBMC approaches with minimal increase in complexity making it a promising candidate for efficient and spectrally contained multicarrier

communications.

However, despite its advantages, PPN-based FBMC design still encounters a few problems in highly frequency-selective channels due to intrinsic interference and equalization challenges [60]. These limitations have motivated further research into alternative FBMC implementations, such as frequency-spreading FBMC, which aim to enhance receiver performance while maintaining acceptable complexity. Consequently, the following section reviews FS-FBMC architectures and recent advancements by focusing on optimizing receiver performance and complexity.

Finding	Limitation	Reference
The short prototype filter reduces FBMC-OQAM filter length while maintaining good spectral performance.	A shorter filter may reduce frequency selectivity and interference suppression.	57
Hopping DFT reduces the computational complexity of the FS-FBMC receiver.	The method mainly focuses on receiver complexity and not BER or PAPR reduction.	58
Jointly optimized prototype filters improve the performance of PPN-based QAM-FBMC.	The filter optimization increases design and implementation complexity.	59
The real-interference prediction algorithm improves MIMO FBMC-OQAM equalization performance.	Its accuracy depends on reliable interference and channel estimation.	60

2.4.2 Frequency Spreading

Technically, FBMC has two different approaches for FBMC design which are frequency spreading (FS) and Polyphase network (PPN). Based on real multiplications required for filters, frequency shifting, IFFT and FFT operations in FBMC, derivation of complexity can be made thoroughly. The authors in [61] state that although conventional PPN has slightly low complexity compare to FS however PPN will cause additional transmission delay. A proposed FS with a large IFFT number and two polyphase filterbanks has been introduced by the authors in [62] but the FS implementation is inefficient due to the enlarged IFFT.

Previous studies have emphasized block FS in their research [63]. The method introduced by the authors has the advantage that allowing a double selective channel and spread frequency in time which can reduce latency. FS performs prototype filtering directly in the frequency domain instead of using the traditional PPN. In the FS

structure, each symbol is shaped by distributing its spectral components across several adjacent frequency bins using a predefined set of spreading coefficients derived from the prototype filter's frequency response [64]. This allows the transmitter and receiver to implement filtering through efficient FFT and IFFT operations rather than long convolution processes. FS filtering produces sharper subcarrier localization and reduced out-of-band (OOB) emissions [65]. Another advantage is its improved robustness of MIMO system design. The FS structure essentially performs the filtering operation in a wide frequency domain by using a large FFT. This provides a clear, high-resolution view of the signal spectrum, which facilitates efficient and simple per-subcarrier channel estimation and equalization. FS implementation's in frequency-domain processing allows for more manageable handling of ISI and ICI, especially when integrated into complex MIMO channel scenarios.

More analysis is required to understand more completely about the reduction of complexity in FS-FBMC. An additional multiplication method (AMM) for the algorithm will be proposed in this research to overcome this problem. The main idea is to use less multiplication and more additional of operations in the algorithm. This is because theoretically, multiplication can cause high complexity compared to an additional operation [27]. Figure 2.2 and Figure 2.3 below are basic principles of FS-FBMC part at transmitter and receiver [37].

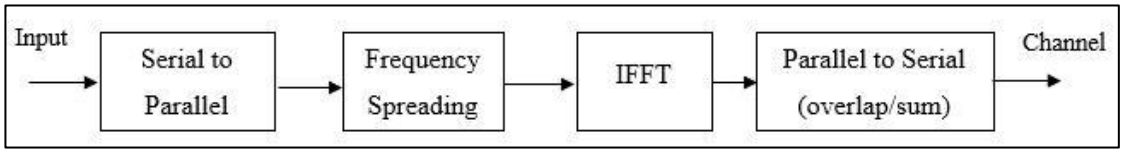

Figure 2.2 FS-FBMC Transmitter

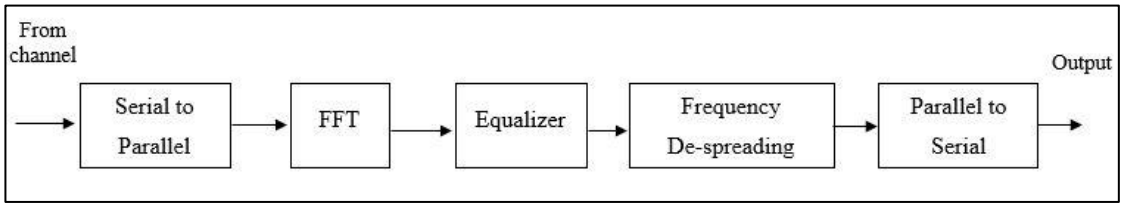

Figure 2.3 FS-FBMC Receiver

The FS framework was selected over the PPN framework because it provides a more suitable structure for the proposed MIMO FBMC system. Its frequency-domain implementation enables direct integration of the AMM algorithm within the spreading process. Unlike existing FS-FBMC studies that mainly focus on waveform implementation or spectral performance, this research extends the FS structure into an integrated framework that simultaneously addresses PAPR reduction, processing-time improvement and ISI suppression.

Finding	Limitation	Reference
The proposed transmitter structure reduces the computational complexity of FBMC.	It focuses mainly on transmitter complexity and not BER or PAPR performance.	62
Block frequency spreading enables low-complexity MIMO implementation in FBMC-OQAM.	Its performance may depend on accurate channel estimation and synchronization.	63
FBMC offers high spectral efficiency, low out-of-band emission and good support for future wireless systems.	The study is mainly an overview with limited practical validation.	64
FBMC provides better spectral containment and interference reduction than conventional multicarrier systems.	The study uses limited simulation conditions and does not consider advanced MIMO equalization.	65

2.4.3 Offset Quadrature Amplitude Modulation (OQAM)

Filter Bank Multicarrier with Offset Quadrature Amplitude Modulation (FBMC/OQAM) is widely recognized as a strong candidate for beyond-OFDM multicarrier modulation, particularly due to its enhanced spectral characteristics, elimination of CP and high resistance to synchronization errors. However, these advantages are accompanied by challenges such as intrinsic imaginary interference, increased complexity and significant difficulties in integrating MIMO systems. Recent literature addresses these limitations from various perspectives, including prototype filter (PF) design, frequency-spread based implementations and the development of robust algorithms.

The studies show substantial progress but also reveal critical gaps that motivate further research. These authors proposed one of the most comprehensive analyses of prototype PF for FBMC/OQAM [66]. A key contribution of this study was the

introduction of new Nyquist-based pulses. These filters demonstrated improved ISI mitigation, narrower sidelobes, and better out-of-band radiation performance. The authors also address one major weakness of FBMC/OQAM is its difficulty in supporting MIMO transmission. Although the research provides extensive comparison across multiple performance indicators, the study focuses on moderate channel conditions and does not fully address double-selective channels.

Khrouf et al. [67] provided the first mathematically signal to interference plus noise ratio (SINR) expressions for discrete-time FBMC/OQAM systems. The authors derived two complementary SINR formulations. One optimized with the receiver waveform, and the other with respect to the transmitter waveform. Their results confirmed that FBMC/OQAM consistently achieves superior SINR performance compared to FBMC/QAM. However, the study focused solely on SISO systems and MIMO performance remains unaddressed.

This paper introduced a fundamentally new approach to designing short PF optimized for 5G low-latency applications [57]. The authors introduced the Near-Perfect Reconstruction (NPR1) filter, developed by applying time and frequency inversion techniques. Using both PPN and FS implementations, the authors showed that NPR1 exhibits improved robustness against timing offset, frequency offset, and multipath fading when compared to existing short PF. Despite good performance, the research does not explore MIMO performance with the NPR1 filter. Besides that, short PFs inherently compromise spectral localization compared to long filters.

OQAM preprocessing and postprocessing were introduced in the system to minimize interference between subcarriers. Normal QAM modulated in-phase (I) and quadrature (Q) simultaneously while offset QAM delays Q by half the symbol period of component I. This process ensures that real and imaginary will execute separately. The equation below generates $a_{m,n}$ as real OQAM symbols [68];.

$$a_{m,n} = \begin{cases} d^{R}_{m,\frac{n}{2}} & n\ even \\ d^{I}_{m,\frac{n-1}{2}} & n\ odd \end{cases}. \tag{2.4}$$

Where d^R is real component while d^I is imaginary component, m is subcarrier index and n is OQAM time slot. When n is even, real part is transmitted and while m is odd, imaginary part is transmitted.

Finding	Limitation	Reference
The short prototype filter reduces FBMC-OQAM filter length while maintaining good spectral performance.	The filter design may increase complexity and requires careful parameter selection.	57
Pulse-shaping filters improve spectral efficiency and reduce out-of-band emission in FBMC-OQAM.	Performance depends strongly on the selected filter and channel conditions.	66
FBMC-OQAM generally provides better SINR than FBMC-QAM under comparable conditions.	The study mainly focuses on SINR and does not examine PAPR or computational complexity.	67

2.5 Performance of Peak Average Power Ratio (PAPR)

All multicarrier modulation suffers from high PAPR and FBMC is not exceptional. Signal clipping and other nonlinear distortions may occur in FBMC signals when the PAPR is excessively high [69]. Large peak amplitudes can drive the power amplifier into its nonlinear operating region leading to signal degradation and performance loss. There is notable classifications to reduce PAPR for OFDM which are clipping, companding, filtering and selected mapping. Although FBMC employs well-designed prototype filters and does not require a cyclic prefix, the use of multiple subcarriers still causes constructive interference in the time domain, leading to large signal peaks.

In some cases, the PAPR of FBMC can exceed OFDM due to the overlapping nature of the filter responses and the OQAM processing structure. As a result, high PAPR degrades the efficiency of power amplifiers, increases the likelihood of nonlinear distortion, and reduces the overall energy efficiency of the communication system. Ultimately, the choice of PAPR reduction method in FBMC follows the same design commonly encountered in OFDM which are reduction in computational complexity, possible data rate loss, the need for side information, and potential BER degradation.

2.5.1 Synchronization

Synchronization in FBMC systems remains a challenging task due to the absence of a cyclic prefix and the use of long, overlapping prototype filters. Unlike OFDM, where cyclic prefix can help suppress synchronization errors FBMC is highly sensitive to both timing and frequency misalignments, which directly disrupt the real-field orthogonality of subcarriers. This lack of a guard interval, combined with the summation of multiple subcarriers, also results in a high PAPR.

Existing synchronization approaches for FBMC often adapt OFDM-based techniques through modified preamble designs or pilot-assisted schemes. However, many of these methods assume ideal channel conditions and focus primarily on synchronization accuracy without sufficiently addressing the impact on system-level performance metrics such as BER and PAPR [70]. In practical scenarios, timing offset causes misalignment between the received signal and the analysis filter bank. It can lead to high intrinsic interference and become worse in multipath channels. Simultaneously, high PAPR introduces non-linear distortions that significantly degrade the BER and create out-of-band radiation.

Synchronization issues further influence FBMC system performance as accurate timing and frequency alignment are essential to minimize intrinsic interference in FBMC systems. Any timing offset or frequency mismatch can lead to performance degradation, increased error rates, and reduced spectral efficiency. For example, Zheng et al. proposed a timing synchronization algorithm for FBMC systems based on a phase-weighted conjugate symmetric structure [71]. The main idea of the method is to use the conjugate symmetry property of FBMC signals and apply phase weighting to obtain a clearer timing metric. This helps improve the accuracy of timing offset estimation, especially in the presence of noise and intrinsic interference, which are common in FBMC systems due to the absence of a cyclic prefix. Simulation results show that the proposed algorithm performs better than conventional correlation-based timing methods, particularly at low SNR values. The algorithm becomes more practical because it does not require extra pilot symbols. However, the study mainly focuses on timing estimation accuracy and provides limited discussion on BER performance in multipath channel conditions.

Authors in [72] proposed an improved timing synchronization algorithm for FBMC-OQAM systems based on the use of a training sequence. The method introduces

a designed training sequence to enhance the timing metric and reduce the effect of intrinsic interference caused by overlapping FBMC symbols. By exploiting the known structure of the training sequence at the receiver, the proposed algorithm achieves more accurate timing offset estimation compared to conventional synchronization methods. Although the proposed method can improve timing synchronization, it can also increase system overhead and reduce spectral efficiency.

This research proposed time and frequency synchronization issues in FBMC Coordinated Multi-Point (CoMP) transmission [73]. The paper highlights that synchronization becomes more challenging in CoMP systems because multiple base stations must be synchronized in both time and frequency to avoid severe interference at the receiver. The authors show that FBMC is particularly sensitive to synchronization errors in CoMP scenarios due to its overlapping symbol structure and the absence of a cyclic prefix. Their results indicate that even small timing or frequency mismatches between cooperating transmitters can lead to significant performance degradation. Although the study provides valuable insight into synchronization requirements for CoMP-FBMC systems, it mainly focuses on system-level synchronization constraints and does not deeply analyze the impact of timing errors on BER performance.

Many existing methods introduce additional overhead, high computational complexity, overlapping symbol blocks or rely on ideal channel assumptions. In addition, several synchronization and PAPR reduction techniques achieve performance improvements only under controlled conditions and do not sufficiently evaluate the impact of residual timing offset and PAPR suppression on BER performance. These limitations indicate a critical need for robust and low-complexity solutions that can effectively reduce timing offset and minimize PAPR without causing excessive BER degradation.

Finding	Limitation	Reference
The phase-weighted conjugate symmetric structure improves timing synchronization accuracy in FBMC systems.	It focuses only on timing synchronization and requires a specially designed training structure.	71
The improved training-sequence method provides more accurate timing estimation for FBMC-OQAM.	The training sequence creates additional transmission overhead.	72
Joint time and frequency synchronization supports coordinated multipoint transmission using FBMC.	It focuses specifically on CoMP systems and requires coordination between multiple transmitters.	73

2.5.2 PAPR Reduction Technique

PAPR is a major drawback in multicarrier communication systems, including FBMC, as it reduces power efficiency and degrades transmitter performance. High PAPR causes power amplifiers to operate in the nonlinear region, leading to signal distortion and reduced system reliability. Therefore, various PAPR reduction techniques have been widely studied to improve signal quality, enhance power efficiency, and ensure reliable transmission in next-generation wireless communication systems.

2.5.2.1 Clipping Method

Some PAPR schemes such as iterative clipping have been suggested for the FBMC system because classical schemes proposed for OFDM cannot be directly applied to FBMC [74]. The clipping method is one of the simplest and most widely adopted PAPR reduction techniques for multicarrier systems where the signal amplitude is deliberately limited to a predefined threshold before transmission. Although clipping was originally developed for OFDM, it has also been extended to FBMC due to its straightforward implementation and ability to provide immediate and significant PAPR reduction. Previous researchers in [75] also proposed iterative clipping filtering method with a combination of bilayer partial transmit sequence. Although the result shows remarkable improvement however number of subcarriers only limited to 128 and it can only use 4 QAM as a system parameter which is not compatible for a 5G network.

The authors in [76] analyze the effectiveness of clipping techniques in reducing

PAPR of higher-order Universal Filtered Multicarrier System (UFMC) QAM systems designed for 5G NR. The study evaluates how different clipping levels influence key performance metrics such as PAPR reduction, BER and spectral characteristics when higher order QAM modulation is employed. Simulation results show that clipping can significantly lower PAPR but with a lower order of QAM, making system less practical for 5G networks. Besides that, excessive clipping can introduce distortion that degrades BER and spectral performance.

Although sometimes clipping can affect the performance of the system, in the context of FBMC, this method can help to suppress excessively high signal peaks that arise from the overlapping subcarrier filters and OQAM processing structure. This reduction in PAPR improves the efficiency of the power amplifier, reduces the risk of nonlinear distortion, and enhances the overall energy efficiency of the transmitter. However, despite these benefits, clipping still introduces in-band distortion and may degrade BER performance if not combined with suitable filtering or companding techniques. Therefore, recent studies on FBMC increasingly explore hybrid methods such as clipping-and-filtering and iterative clipping [77].

The authors in [78] proposed a new form of the filter bank multi-carrier spread spectrum (FBMC-SS) waveform. This new waveform modifies the filtered multi-tone spread spectrum (FMT-SS) system and is intended to whiten the power spectral density (PSD) of the transmit signal. Clipping was applied to further reduce PAPR in their new overlapped FMT-SS and the result shows that clipping successfully minimizes PAPR with minimal impact on its performance.

Finding	Limitation	Reference
The joint optimization scheme reduces PAPR more effectively	It requires additional optimization and filtering processes.	75
Clipping reduces the PAPR of higher-order UFMC-QAM signals.	Strong clipping increases signal distortion and worsens BER.	76
Combining low-complexity selective mapping with clipping and filtering provides better PAPR reduction for FBMC-OQAM.	The combined technique still increases processing complexity.	77
Overlapping subbands improve spectral usage, flatten the signal spectrum and can provide low PAPR.	The method requires interference cancellation between overlapping subbands.	78

2.5.2.2 Filtering Technique

Addressing high PAPR in FBMC, filtering based approaches have also been widely studied as they can shape the transmitted signal and suppress large amplitude peaks without requiring significant changes to the transmitter structure. By appropriately designing or modifying the prototype filter, these methods aim to reduce signal fluctuations while preserving spectral efficiency and maintaining low out-of-band emissions [79].

The research input by authors in [80] focuses on improving the performance of FBMC systems in 5G environments where user mobility causes Doppler shift. Doppler effects can distort the transmitted signal and degrade system reliability, especially at higher speeds. To address this issue, the authors propose a modified filtering approach within the FBMC framework that is better suited to time-varying channels. The improved filter design helps reduce the impact of Doppler spread, leading to lower interference and more stable signal reception.

A previous study has explored the use of improved filtering techniques in FBMC and UFMC systems to enhance performance in 5G communications[81]. For FBMC, the author uses binomial prototype filter to provide better signal quality than the commonly used PHYDYAS filter especially when higher modulation levels are applied. For UFMC, alternative prototype filters have also shown the ability to slightly reduce signal power fluctuations compared to traditional filtering methods. These results indicate that suitable filter design can support higher data rates while improving overall signal behavior. However, the improvements are generally limited and may involve increased design complexity

Authors in [82] analyze the application of an iterative basic clipping and filtering technique to reduce the high PAPR inherent in FBMC systems. The proposed method repeatedly clips the signal peaks and applies filtering to limit distortion and spectral spreading. Simulation results indicate that the iterative process can achieve noticeable PAPR reduction while maintaining acceptable signal quality and spectral characteristics. The study also stated that the technique is simple to control PAPR in FBMC systems, making it a practical option for multicarrier transmission schemes. However, the analysis is limited and does not consider system complexity.

Finding	Limitation	Reference
The modified filtering method reduces Doppler effects in FBMC communication.	It mainly focuses on Doppler reduction and does not study MIMO or PAPR.	80
Binomial and fractional-powered binomial filters improve the filtering performance of FBMC and UFMC.	The study has limited simulation and practical implementation analysis.	81
Iterative clipping and filtering effectively reduces the PAPR of FBMC signals.	Repeated iterations increase processing complexity and may introduce signal distortion.	82

2.5.2.3 Hybrid Clipping and Filtering Technique

Another approach by researchers is combination of clipping and filtering (CF) to reduce PAPR in the system. The author in [79] investigated the integration of MIMO with QAM-FBMC to address interference and high PAPR challenges in multicarrier systems. The research first analyzed the performance of MIMO QAM-FBMC in terms of complexity, interference, and spectral efficiency, highlighting that although FBMC offers better spectral containment and higher throughput than OFDM, it still suffers from high PAPR especially when nonlinear power amplifiers are considered. To overcome this issue, a novel PAPR reduction technique based on clipping and filtering mapped onto the null space of the MIMO channel was proposed. By projecting the PAPR reduction signals into the channel null space, the method effectively reduced input back-off (IBO) while suppressing interference caused by the PAPR processing. Simulation results demonstrated significant PAPR reduction, improved throughput, and better performance compared to conventional clipping and filtering methods, particularly in frequency-selective fading environments. However, the research shows limited discussion on computational cost, scalability to higher MIMO configurations, and practical hardware constraints. Therefore, further research is required to develop low-complexity and more robust PAPR reduction methods that can operate efficiently under realistic channel estimation errors and larger MIMO systems.

Similarly, the authors in [83] focused on mitigating the inherent high PAPR problem in FBMC/OQAM systems. The authors proposed a hybrid SCaF-PTS technique that combines selective iterative clipping and filtering (SCaF) with the Partial Transmit Sequence (PTS) method. Unlike conventional single-technique approaches, this hybrid method applies multiple stages of clipping and filtering followed by

optimized phase rotation using PTS to further suppress signal peaks. Simulation results showed that the proposed SCaF-PTS scheme achieved substantial PAPR reduction up to approximately 11 dB, outperforming standalone CaF and PTS techniques. However, the improvement in PAPR performance was obtained at the cost of increased computational complexity and noticeable BER degradation particularly when higher clipping ratios were used.

This work [84] extends previous research on hybrid PAPR reduction methods by integrating low-complexity techniques within MIMO-FBMC framework. The authors addressed the high PAPR issue in MIMO FBMC/OQAM systems by proposing a hybrid technique that combines Repeated Clipping and Filtering (RCF) with several nonlinear companding schemes, including Mu-Law, A-Law, tangent rooting, logarithmic rooting, cos, and rooting companding. The study first stated that although FBMC/OQAM offers high spectral efficiency and robustness against ICI and ISI, it inherently suffers from large peak amplitudes that drive the high-power amplifier (HPA) into the nonlinear region, resulting in in-band (IB) and out-of-band (OOB) distortions that degrade BER performance. The authors implemented a 2×2 MIMO configuration and applied iterative RCF to suppress regenerated peaks to overcome this problem, followed by nonlinear companding to further compress signal amplitudes while compensating BER degradation caused by clipping. Simulation results demonstrated a significant PAPR reduction with the RCF and Mu-Law combination providing the best trade-off between PAPR reduction and BER performance. However, the study is limited to specific companding parameters while the impact of higher order MIMO systems, different channel conditions, and overall system complexity is not fully explored.

Finding	Limitation	Reference
The proposed precoding method improves BER and reduces PAPR in MIMO QAM-FBMC systems.	It requires channel information and additional precoding calculations.	79
Combining iterative clipping and filtering with PTS provides better PAPR reduction in FBMC/OQAM.	The combined method increases computational complexity and may require side information.	83
Repeated clipping and filtering with nonlinear companding reduces PAPR in MIMO FBMC/OQAM while improving BER performance.	Repeated filtering and companding increase processing complexity and require proper parameter selection.	84

2.5.2.4 μ-Law Companding Technique

Another effective distortion-based PAPR reduction technique that has gained attention for FBMC systems is μ-law companding which is a nonlinear amplitude compression method originally used in audio signal processing. When applied to FBMC, μ-law offers a significant advantage because the high time-domain fluctuations caused by the overlapping filter responses can be effectively suppressed without severely impacting the orthogonality of the OQAM structure.

In 2018, Boyapati and Prema analyzed all popular PAPR reduction techniques employed for OFDM and applied a few of them on the basic FBMC system [16]. The results show that basic selective mapping has the lowest PAPR followed by μ-law methods and partial transmit. However, selective mapping technique results reduced data rate and complex to implement. μ-law was simple and easy to implement but came with the cost of degradation of BER performance. Nevertheless, the BER performance of μ-law can still be improved. Recent research shows that authors in [85] proposed hybrid approach that combines an enhanced version of μ-law companding (EMLC) with Tone Reservation (TR) to mitigate PAPR effectively. The simulation results indicate that the hybrid approach effectively reduces PAPR while maintaining overall system performance, making it a promising solution for achieving high efficiency in 5G communication networks.

Authors in [86] proposes logarithmic rooting companding as an effective technique to PAPR in FBMC-OQAM systems and analyze the result by including μ-law, A-law and tangent rooting method. The main idea is to compress the amplitude of high-power signal peaks using a logarithmic function before transmission and preserve

the lower-power components. At the receiver, an inverse operation is applied to recover the signal. Simulation results show that the proposed method achieves noticeable PAPR reduction compared to the conventional FBMC-OQAM system, without introducing excessive distortion or requiring complex signal processing. Unlike some existing PAPR reduction techniques, this approach does not rely on side information and keeps the system structure simple. Although the proposed method looks simple and suitable for practical applications, the nonlinear nature of companding may still introduce signal distortion and BER degradation. Further optimization is needed to balance PAPR reduction and system performance.

The proposed JOS method combines clipping and μ-law companding because each technique addresses a different part of the high PAPR problem. Clipping removes extreme signal peaks while μ-law companding compresses the overall amplitude range and reduces the occurrence of large peaks. Their integration enables stronger PAPR reduction than either technique alone. As a result, JOS provides a practical balance between PAPR performance, signal distortion and processing requirements.While clipping and filtering widely used to reduce high PAPR for OFDM system by researchers in [19][87][88], there is no information available on hybrid clipping with μ-law for FBMC system.

Finding	Limitation	Reference
The study compares several PAPR reduction methods for FBMC and identifies the technique with better PAPR performance.	It mainly focuses on PAPR comparison with limited BER and complexity analysis.	16
Combining enhanced μ-law companding with tone reservation reduces PAPR while maintaining BER and spectral performance.	Tone reservation uses some subcarriers and increases signal-processing complexity.	85
Logarithmic rooting companding achieves better PAPR reduction than conventional companding methods.	The improved PAPR causes BER degradation, requiring a trade-off between PAPR and BER.	86

2.5.2.5 A-Law Companding Technique

Another nonlinear companding method to minimize PAPR is A-Law which is quite known among researchers due to its effectiveness. Authors in [89] introduced a PAPR reduction approach that combines Discrete Sine Transform (DST) precoding with A-law nonlinear companding. In their method, DST precoding helps spread the signal energy more evenly, while A-law companding is used to limit high signal peaks. The results show that this combined approach can effectively reduce PAPR with only a small impact on error performance. However, because companding alters the original signal shape, the chosen parameters strongly influence its performance, and inappropriate settings may lead to increased distortion, highlighting the need for simpler and more robust PAPR reduction solutions.

Neenu Raju and Dr. Sakuntala S. Pilla in [90] proposed PAPR reduction in FBMC systems by combining nonlinear companding with pulse shaping techniques. The authors applied A-Law method to compress high-amplitude signal peaks. Raised Cosine pulse shaping is used to control the time-domain waveform and reduce peak formation caused by the intrinsic symbol overlapping in FBMC systems. Simulation results show that the combined technique achieves noticeable PAPR reduction compared to conventional FBMC systems with only a minor degradation in BER performance. The study demonstrates that integrating pulse shaping with companding provides a simple and effective means to improve transmitter power efficiency. However, the performance of companding based approaches is highly dependent on the choice of parameters and pulse shaping filters. Excessive nonlinear processing may introduce signal distortion and BER degradation.

Researchers in [15][16][91] presented a comprehensive investigation of various PAPR reduction techniques applied to FBMC systems. Their work reviews and evaluates commonly used PAPR reduction methods, such as clipping, companding, and transform-based techniques, to understand their effectiveness and limitations in the FBMC framework. The study highlights that although many conventional PAPR reduction methods originally developed for OFDM can be adapted to FBMC, their performance is often affected by the symbol overlapping and filtering structure of FBMC systems. Simulation results show that while certain techniques can achieve noticeable PAPR reduction, they may also introduce signal distortion or degrade error performance if not carefully designed. Overall, the paper emphasizes the trade-off

between PAPR reduction capability, system complexity, and BER performance, and points out the need for more PAPR reduction techniques specifically focused on FBMC systems.

Another hybrid method for PAPR reduction in FBMC-OQAM systems was proposed in [92] where Tone-Selected Partial Transmit Sequence (TSLM) is combined with A-law. In this approach, the TSLM technique is first used to reduce signal peaks by selecting a suitable transmit sequence, while A-law companding is applied to further suppress the remaining high-amplitude components. Simulation results show that the hybrid scheme achieves improved PAPR reduction compared to using TSLM or companding alone. However, the process increases computational complexity and requires additional processing, which may limit its suitability for low complexity or real time FBMC-OQAM systems.

Finding	Limitation	Reference
Combining DST precoding with A-law companding provides better PAPR reduction in FBMC/OQAM.	The combined technique adds processing complexity and may affect BER.	89
Companding and pulse-shaping techniques reduce PAPR in FBMC systems.	Performance depends on the selected companding method and pulse-shaping filter.	90
Among the evaluated companding methods, μ-law provides the best PAPR, BER and PSD performance.	Proper parameter selection is required to balance PAPR reduction and BER.	91
Combining TSLM with A-law companding improves PAPR reduction in FBMC/OQAM.	The hybrid method increases computational complexity and may require side information.	92

2.6 Computational Complexity in Multicarrier Systems

Computational complexity remains a central design metric in modern multicarrier systems, especially as 5G and beyond networks demand high-throughput and real-time baseband processing [93]. Although OFDM maintains low complexity due to its reliance on FFT/IFFT operations with $O(N\log N)$growth, recent studies illustrate that emerging waveforms such as FBMC-OQAM impose significantly higher processing load owing to prototype filtering and OQAM staggering. The PPN structure of conventional FBMC requires multiple filtering stages proportional to filter length, increasing the number of real multiplications and additions compared with OFDM [94].

In order to overcome this challenge, the research regarding FS-FBMC has gained attention for its reduced computational cost, as filtering is performed in the frequency domain using block-based operations, making it far more suitable for hardware implementation [63]. Nevertheless, when FBMC is extended to MIMO scenarios, complexity further rises because the absence of a cyclic prefix demands advanced equalization and intrinsic interference mitigation techniques [95]. These developments prove that while FBMC and FS-FBMC offer significant spectral and interference-related advantages, achieving low computational complexity remains a key challenge for their practical adoption in MIMO and future 6G systems.

2.6.1 Complex Multiplication Method

Complexity is one of the issues among modulation techniques. Complex multiplication is a core operation in multicarrier systems, especially in FBMC, FS-FBMC, MIMO equalizers, and adaptive filtering, making its computational complexity a critical design factor. The conventional complex multiplication requires four real multiplications and two additions, which becomes costly when implemented across thousands of subcarriers or in systems with high-order MIMO processing [96]. Based on real multiplications required for filters, frequency shifting, IFFT and FFT operations in FBMC, derivation of complexity can be made thoroughly.

More analysis is required to understand more completely about the reduction of complexity in FS-FBMC. An additional multiplication method (AMM) for the algorithm will be proposed in this research to overcome this problem. The main idea is to use less multiplication and more additional of operations in the algorithm. This is because theoretically, multiplication can cause high complexity compared to additional operations [27].

Standard complex multiplication executes 4 multiplications and 2 additions. It is also straightforward and appears in MIMO matrix multiplication, complex prototype filter bank and subcarrier equalization.

Let two complex numbers be [97];

$$x = a + jb, y = c + jd \tag{2.5}$$

with real parts a, c and imaginary parts b, d. Their product $z = x \cdot y$ is:

$$z = (a + jb)(c + jd)$$

Expand using distributivity:

$$z = ac + ajd + jbc + j^2bd.$$

Since $j^2 = -1$,

$$z = (ac - bd) + j(ad + bc).$$

So the real and imaginary parts are

$$\mathrm{R}\{z\} = ac - bd, \mathrm{I}\{z\} = ad + bc \tag{2.6}$$

To compute these, we need the four real multiplications

$$m_1 = a \cdot c, m_2 = b \cdot d, m_3 = a \cdot d, m_4 = b \cdot c,$$

and then the two real additions (one subtraction):

$$\mathrm{I}\{z\} = m_1 - m_2, \mathrm{I}\{z\} = m_3 + m_4 \tag{2.7}$$

Thus, the implementation uses 4 real multiplications and 2 real additions (counting subtraction as an addition. This if for a single complex multiply $(a + jb)(c + jd)$:
For Nindependent complex multiplies (per-subcarrier operations for Nsubcarriers) the equation above proved that Multiplications is $4N$ and Additions is $2N$.

2.6.2 Karatsuba Method

Another method that can help to reduce complexity is Karatsuba. Authors in [98] proposes an enhanced high-speed modular multiplier using the Karatsuba algorithm to improve parallel processing efficiency in cryptographic applications. The authors integrate Karatsuba multiplication with Barrett reduction and Montgomery modular multiplication within a digit-serial architecture to reduce arithmetic complexity. By splitting operands into MSB and LSB components and computing partial products in parallel, the conventional multiplication complexity is reduced from $O(n^2)$ to $O(n^{log_2{}^3})$. The study emphasizes that Karatsuba multiplication enhances critical path performance by minimizing the number of sub-word multiplications

making it suitable for cryptographic systems that require high-speed encryption and decryption process.

Building upon the concept of Karatsuba-based acceleration, authors in [99] extend its application to elliptic curve pairing computation, particularly for 128-bit secure R-ate pairing in identity-based cryptography . Compared to the earlier modular multiplier focus, this work integrates a 256-bit Karatsuba-based multiplier within a layered parallel architecture over extension fields. The divide-and-conquer principle is leveraged to accelerate multiplication in finite field arithmetic, significantly reducing execution time when implemented on FPGA platforms. By using OpenCL, the system demonstrating that Karatsuba multiplication is highly effective for large-bit cryptographic operations.

Further study into Karatsuba algorithms is presented by authors in [100] who compare Vedic and Karatsuba algorithms for 64-bit Barrett modular multiplication. The study highlights that modular multiplication consists of two key components integer multiplication and modular reduction. Barrett reduction is used to improve hardware efficiency. The Vedic multiplier achieves higher operating frequency due to greater DSP utilization while the Karatsuba-based design demonstrates better throughput indicating superior efficiency. The results show that algorithm selection significantly influences trade-offs between speed, area utilization, and resource consumption in FPGA implementation.

A comprehensive review of the Karatsuba algorithm has been provided by authors in [101] emphasizing its theoretical advantage over classical multiplication methods. The review confirms that Karatsuba reduces multiplication complexity from $O(n^2)$ to $O(n^{1.585})$ using a recursive divide-and-conquer approach, making it highly suitable for large-bit arithmetic operations common in DSP and cryptographic systems. The study further discusses that Karatsuba improves processing speed while reducing the number of required multiplications, albeit at the cost of additional additions. These works establish that although Karatsuba provides computational complexity reduction and hardware efficiency benefits, its practical performance depends on choices of architectural design.

Finding	Limitation	Reference
The Karatsuba modular multiplier improves multiplication speed and reduces hardware delay.	The recursive structure increases addition operations and hardware control complexity.	98
The Karatsuba-based accelerator speeds up pairing computations used in cryptographic systems.	It is designed mainly for cryptographic applications rather than wireless communication systems.	99
Karatsuba multiplication provides good speed and hardware efficiency for 64-bit Barrett modular multiplication.	Its performance depends on the operand size and hardware architecture used.	100
Karatsuba reduces the number of multiplication operations for large integers compared with conventional multiplication.	It requires more addition operations and may not be efficient for small input sizes.	101

2.6.3 Time Complexity Method

Although FBMC modulation is widely regarded as a promising waveform for future 5G systems, but its complexity remains a significant challenge. Authors in [62] compares the two main FBMC implementation which are Frequency Spreading (FS) and Polyphase (PP) by focusing on computational complexity and quantization effects. The authors also propose an alternative FBMC transmitter design that reduces complexity by replacing full-size IFFTs with half-size IFFTs using real-valued signal processing. The results show that this approach can significantly reduce processing requirements while maintaining performance. It also exhibits lower quantization error, which is particularly important for low-cost and low-precision hardware implementation

Recent research shows that FBMC can be a strong alternative to OFDM for short-reach optical communication systems because it uses bandwidth more efficiently and produces less unwanted spectral leakage [102]. However, conventional FBMC transmitters rely on FFT-based structures, which lead to high implementation complexity, especially at high data rates. To address this, the authors propose a simplified real-time FBMC transmitter that reduces FFT complexity and overall hardware requirements. Although experimental results demonstrate that the proposed FBMC design reduce latency and increase the data rates, however the research mainly focuses on practical hardware implementation and did not discuss performance

comparisons under different system conditions.

This paper compares FBMC and OFDM as candidate waveforms for 5G wireless communication systems, highlighting their key strengths and limitations [103]. The authors show that FBMC offers better spectral efficiency and lower out-of-band leakage than OFDM, making it more suitable for scenarios with strict bandwidth constraints. However, the study also points out that FBMC comes with higher implementation complexity compared to OFDM, which remains attractive due to its simplicity and mature hardware support. Authors concluded that while OFDM is easier to implement, FBMC has strong potential for future 5G applications where efficient spectrum usage is a priority.

This paper presents a comparative study of computational complexity based on several multicarrier modulation [104]. The authors analyze the processing requirements of different waveform candidates, highlighting that FBMC can achieve better spectral properties than OFDM. However, these performance improvements are generally accompanied by a significant increase in computational complexity, particularly in filter bank processing and signal reconstruction stages. Although FBMC initially appears much more complex than CP-OFDM, this difference becomes less significant when the overall system requirements are considered. During this time, factors such as channel coding and iterative decoding play an important role in the total computational load.

The authors in [60] propose a real interference prediction (ERIP) algorithm that relies on real-valued processing to improve equalization performance. A comparison with a parallel multistage equalizer shows that the proposed method can be more computationally efficient when channel conditions remain stable over multiple FBMC-OQAM symbols. Simulation results show that the proposed method improves detection performance in MIMO FBMC-OQAM systems while keeping complexity at a manageable level. The authors also suggest that the proposed approach is well suited for MIMO FBMC systems where reduced complexity is critical. However, the need to repeatedly compute correlation coefficients limits its practicality in fast-fading channels.

Finding	Limitation	Reference
Interference prediction improves equalization and BER performance in MIMO FBMC-OQAM systems.	It requires channel estimation and additional interference calculations.	60
The proposed transmitter structure significantly reduces FBMC computational complexity.	It focuses mainly on transmitter complexity rather than BER and PAPR.	62
A low-complexity real-time FBMC transmitter improves spectral efficiency in optical IMDD systems.	It is designed for optical communication and may not directly represent wireless FBMC systems.	102
FBMC provides lower out-of-band emission and better spectral efficiency than OFDM.	FBMC requires more complex filtering and has difficulties with MIMO implementation.	103
The study compares the computational requirements of different multicarrier physical-layer techniques.	It mainly provides theoretical complexity analysis with limited practical implementation results.	104

2.7 Intersymbol Interference (ISI)

Intersymbol interference (ISI) is unavoidable in both wired and wireless communication systems because it is linking to the characteristics of the transmission medium and the distance which the signal propagates. In wireless environments signal propagation is particularly affected by fading and multipath delay spread. This happen due to multiple delayed copies of the transmitted signal arrive at the receiver. The presence of ISI significantly increases the probability of symbol detection errors and degrades overall system performance [105]. This degradation occurs because symbols overlap in time, causing the current symbol to be distorted by residual components of previous symbols in the presence of noise. Consequently, extensive research has been conducted to develop effective techniques for mitigating ISI in wireless communication system.

This author [106] analyzed the ability of OFDM to reduce ISI by transmitting data over an additive white Gaussian noise (AWGN) channel. A cyclic prefix (CP) was inserted into the OFDM frame to preserve subcarrier orthogonality during transmission. The results demonstrated that OFDM, when combined with a CP, is effective in mitigating ISI. This improvement arises because each subcarrier operates at a much lower symbol rate, resulting in symbol durations that are longer than the channel impulse response. To eliminate ISI, the CP also referred to as a guard interval must

exceed the maximum multipath delay. However, the main limitation of the presented simulation is its high computational complexity, which requires significant processing power and long simulation time.

Authors in [105] proposed a high speed and area efficient adaptive equalizer based on the LMS algorithm to mitigate ISI. The LMS equalizer was evaluated using different step-size values to determine the optimal trade-off between convergence and performance. The results showed that a larger step size achieved better performance compared to smaller values. To further reduce computational complexity, the equalizer was developed using a symmetric structure. Both the transmitter and receiver were carefully designed to minimize ISI during data transmission. The proposed model employed a simple, low-complexity LMS algorithm and demonstrated effective ISI reduction. However, despite offering a fast and cost efficient solution for ISI mitigation, the approach exhibited limitations in terms of spectral efficiency.

These authors in [107] employed equalization techniques which are ZF and MMSE to reduce ISI and minimize BER. The results showed that applying either equalizer at the receiver significantly enhanced system performance. However, the ZF equalizer exhibited performance degradation when subcarrier gains were very low, leading to severe noise amplification. In contrast, the MMSE equalizer demonstrated more robust behavior, although its performance gradually approached ZF equalizer as the number of iterations increased. The simulation results confirmed that equalization techniques are effective in mitigating ISI and improving system performance, but they still suffer from limitations related to specific subcarrier conditions and iteration requirements.

In OFDM a CP inserted to convert the channel's linear convolution into a circular convolution, thereby eliminating ISI and allowing simple per-subcarrier equalization, whereas FBMC achieves time–frequency localization through long, overlapping prototype filters (and OQAM staggering), so it does not require a CP. Integrating CP into FBMC most likely has higher spectral efficiency at the cost of more complex equalization and intrinsic interference management.

Unlike OFDM, the FBMC system cannot directly apply CP which can cause high complexity on channel equalization. Although there is a theory for CP-FBMC proposed by authors in [55], it has still not been simulated widely by researchers yet. Authors of the book introduced a better approach where linear convolution is replaced by circular convolution and time domain can be converted to frequency domain if length of CP is

larger than delay spread. Theoretically, ISI is almost completely diminished when adding CP if its in OFDM. Multipath fading observed in the time domain can be transformed into flat fading in the frequency domain through the application of the Fast Fourier Transform (FFT). This transformation simplifies channel characteristics, thereby enabling the equalizer at the receiver to operate more effectively and achieve improved symbol recovery. CP was added at the transmitter and it must be larger than expected delay spread of multipath channel to avoid the symbol interferes with the next symbol [108]. This was because increased CP will absorb all of the ISI components, allowing the actual data symbol to be extracted without any errors. Without CP, the next symbol will carry along multipath with it. CP acted as a guard interval to against timing error results caused by ISI.

In [109], the simulations considered different numbers of antennas for each equalizer to evaluate their impact on system performance. The results indicated that the bit error rate (BER) decreased as the number of antennas increased, demonstrating the benefits of spatial diversity. Among the two equalizers, the MMSE equalizer consistently outperformed the ZF equalizer. This is because the ZF equalizer significantly amplifies noise when attempting to invert channel responses with small magnitudes. MMSE equalizer suppresses both noise and ISI by minimizing their combined power at the output. Nevertheless, although MMSE provides better overall performance, ISI is not completely eliminated from the system.

This paper introduces an iterative interference cancellation (IC) approach to reduce the ISI and ICI present in FBMC/OQAM system [110]. An iterative receiver is developed by combining a maximum likelihood (ML) detector with a low-density parity-check (LDPC) decoder. This design allowing the receiver to gradually improve symbol estimates through repeated decoding and detection. The performance of the proposed method is evaluated under different channel conditions that represent various propagation environments. The bit error performance is then compared with conventional FFT-OFDM system operating over Long Term Evolution (LTE) multipath channels. The results show that FBMC/OQAM can achieve better error performance in many scenarios, but this improvement comes at the cost of increased complexity at the receiver.

Finding	Limitation	Reference
The LMS adaptive equalizer reduces ISI with high speed and low hardware cost.	Its performance depends on the selected LMS step size.	105
OFDM provides good performance over an AWGN channel as SNR increases.	The study only considers AWGN and does not include multipath fading.	106
Equalization and channel coding improve the BER performance of OFDM systems affected by ISI.	It focuses on OFDM and does not examine FBMC or adaptive equalization.	107
Equalization techniques improve OFDM BER under fading channel conditions.	The study uses limited equalizers and simulation conditions.	109
Iterative cancellation with ML detection reduces inherent ISI and ICI in FBMC-OQAM.	Iterative processing and ML detection increase receiver complexity.	110

2.8 Adaptive Algorithm

An adaptive algorithm was proposed to calculate the time variation for DFE to equalize time-varying frequency-selective fading channels. There were a few types of adaptive algorithm that have been widely used in wireless system which are Least Mean Square (LMS) , Recursive Least Square (RLS) and Constant Modulus Algorithm (CMA). Shortcomings of this three basic algorithms has been improved by introducing Normalized Least Mean Square (NLMS), Variable LMS, and Signed Least Mean Square [111]. Adaptive algorithms play a critical role in modern multicarrier systems by enabling equalizers to automatically track and compensate for channel variations without requiring explicit channel knowledge. In OFDM systems, adaptive equalization is essential especially in highly time-varying or frequency-selective fading channels where subcarrier gains rapidly fluctuate. Adaptive algorithms also offer a computational advantage by iteratively updating filter coefficients rather than relying on full matrix inversions, making them suitable for systems with a large number of subcarriers.

The advantages of adaptive algorithms include their ability to learn the channel characteristics, maintain robustness under dynamic fading, and operate efficiently in scenarios where pilot overhead must be minimized. However, several drawbacks have been highlighted in recent studies for example convergence speed may be slow for large equalizer lengths, sensitivity to step-size selection can lead to instability, and performance may degrade when interference is strong or when noise power varies abruptly. These challenges are particularly relevant in multicarrier systems where ICI

and ISI appear due to synchronization errors or insufficient frequency selectivity [112]. While OFDM relies on the CP to mitigate ISI, adaptive equalizers in FBMC encounter a more challenging scenario because FBMC does not employ a CP and utilizes highly overlapping prototype filters. This leads to stronger intrinsic interference between adjacent symbols, requiring adaptive algorithms with improved tracking capability, better interference resilience, and higher numerical stability. As reported in several FBMC studies, adaptive equalizers are crucial for combating OQAM intrinsic interference, residual ISI, and channel dispersion, particularly for FS-FBMC systems where per-subcarrier frequency spreading introduces additional equalization complexity [113].

Despite these challenges, adaptive algorithms remain attractive for FBMC due to their flexibility, relatively low computational cost, and ability to integrate seamlessly with advanced equalizers such as Zero-Forcing (ZF), Minimum Mean Square Error (MMSE), and nonlinear decision-directed structures. Their capability to iteratively refine filter weights makes them suitable for next-generation FBMC systems, especially when combined with MIMO techniques and advanced structures like frequency-spreading equalization.

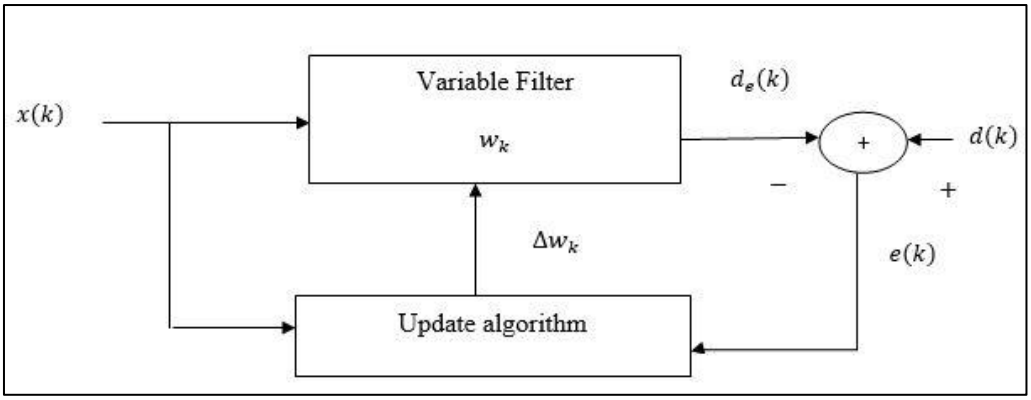

Figure 2.4 General Block Diagram For An Adaptive Filter With Algorithm

Figure 2.4 above shows the general block diagram for Adaptive Filter with Algorithm [114]. The input signal is denoted as x(k) represents the combination of the desired signal d(k) and the noise component v(k). This relationship can be expressed mathematically as follows [114];

$$x(k) = d(k) + v(k) \tag{2.8}$$

The impulse response corresponds to the filter coefficients because the variable filter employs a finite impulse response (FIR) structure. The error signal denoted as e(k) represents the difference between the desired output and the estimated output. It can be expressed mathematically as follows [114] ;

$$e(k) = d(k) - d_e(k) \tag{2.9}$$

The convolution of the input signal with the impulse response provides an estimate of the desired signal in the variable filter [115]. The filter coefficients are updated by the variable filter in real time. Δw_k represents the correction factor applied to these coefficients, which is computed by the adaptive algorithm based on the input signal and the corresponding error signal.

2.8.1 Least Mean Square (LMS)

The Least Mean Square (LMS) algorithm is widely regarded as one of the simplest and most frequently employed adaptive filtering techniques in wireless communication systems [4][111][115]. Its popularity stems from a favorable balance between computational efficiency and performance, making it a preferred choice for real-time applications. LMS updates the equalizer coefficients iteratively based on the instantaneous estimation error, allowing the filter to learn the time-varying channel response. In OFDM systems, LMS is commonly used in adaptive linear equalizers and post-FFT per-subcarrier estimators to combat residual ICI, ISI, phase noise, and channel fluctuations particularly in high-mobility scenarios. Its low complexity makes it attractive for large-scale OFDM deployments where thousands of subcarriers must be equalized simultaneously.

Despite these advantages, LMS exhibits relatively slow convergence compared to more advanced algorithms such as Recursive Least Squares (RLS), particularly in highly dynamic or frequency-selective channels [116]. This limitation arises because LMS relies on a fixed step-size parameter, which can lead to trade-offs between convergence speed and stability, especially when the equalizer length is large or when the channel exhibits severe frequency selectivity. LMS is further affected by noise variance, often leading to steady-state misadjustment. These limitations become more significant in FBMC systems, where the absence of a CP and the use of

overlapping prototype filters create intrinsic interference between adjacent OQAM symbols. As a result, LMS must cope with stronger symbol coupling and increased interference leakage compared to OFDM.

LMS is also frequently integrated with DFE due to its simple coefficient adaptation mechanism. In DFE, LMS updates both feedforward and feedback filters, enabling the equalizer to cancel precursor and postcursor ISI in frequency-selective channels. For OFDM, LMS-DFE can mitigate residual ISI in scenarios of insufficient CP or severe multipath. In FBMC, LMS-DFE is particularly useful because the nonlinear feedback structure helps suppress intrinsic interference and long filter tails produced by prototype filters. Nevertheless, its low complexity and robustness under moderate channel conditions continue to make LMS an attractive solution for adaptive equalization in multicarrier systems.

Previous researchers in [117] applied their neural network algorithm based on mean square error trained by the FBMC system. The authors compared their method with a basic LMS algorithm. The results show slightly better improvement when using the proposed algorithm. However, the length of the training sequence becomes a huge constraint because it can affect the performance of data rate. Abhishek and Sreelakshmi introduced a modified DFE with the presence of LMS in [118] but it cost with high computational complexity although the output proved better analysis in BER.

This author [119] mentioned that any equalizer that uses LMS algorithm needs a prior known symbols in case the decision of the equalizer goes wrong. Besides that, this algorithm also belongs to the family of stochastic gradient algorithms [120]. The objective of this research [121] was to develop a new normalized block LMS for DFE. To achieve improved convergence and effective mitigation of intersymbol interference (ISI), the algorithm was refined to deliver superior steady-state performance. Validation was conducted through Mean Square Error (MSE) analysis, which demonstrated that the normalized LMS algorithm consistently outperformed the conventional LMS approach. This enhancement was realized by normalizing the tap weight vector using the squared Euclidean norm of the input vector, thereby ensuring greater numerical stability and good convergence.

LMS channel estimator was chosen by this author [4] due to its low complexity. The authors discussed about the importance of adaptive modulation and coding for OFDM in order to achieve higher data rates and smaller bit error rate. The LMS estimator provides essential channel state information to the transmitter through

feedback while simultaneously tracking channel variations. This algorithm is commonly integrated with DFE to enhance system performance under various channel conditions.

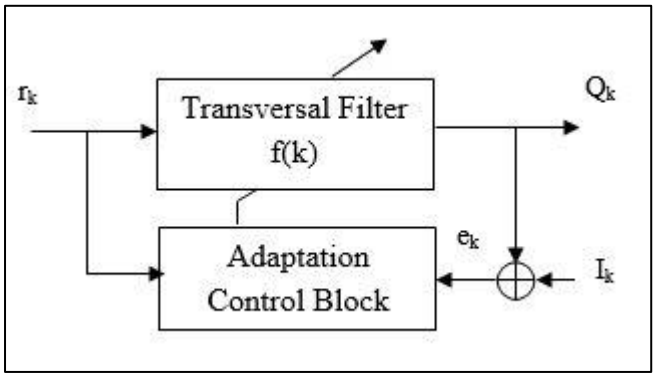

Figure 2.5 LMS Block Diagram

Figure 2.5 shows block diagram for LMS algorithm [122]. The difference between the filter output and the desired response generates an error signal, which serves as the basis for adaptive adjustment. This error, combined with the tap inputs, determines the output of the transversal filter. Tap weights play a critical role in shaping the filter's response, as they define the amplitude and phase characteristics applied to each input sample. By iteratively updating these weights based on the error term, the adaptive filter minimizes distortion, improves convergence, and enhances overall system performance. The equation for LMS algorithm can be written as [121];

$$w(k+1) = w(k) + \mu e(k)x(k) \tag{2.10}$$

$$e(k) = d(k) - w^H(k)x(k) \tag{2.11}$$

Which w (k) as a weight (equalizer) vector at iteration n, x(k) is an input vector, $d(k)$ desired (reference) signal, $e(k)$ as an instantaneous estimation error and μ as a step-size (controls stability and convergence) and w^H is conjugate transpose of weight vector.

Finding	Limitation	Reference
Channel equalization improves the BER performance of MIMO-FBMC systems.	MIMO-FBMC equalization requires additional receiver processing and accurate channel information.	117
DFE reduces ISI and improves the performance of FBMC systems.	Incorrect detected symbols can cause error propagation in the feedback section.	118
Adaptive DFE generally provides better convergence than blind DFE when a training sequence is available.	Adaptive DFE requires training data, while blind DFE may converge slowly.	119
Normalized block LMS-DFE provides faster convergence and better ISI reduction for high-data-rate communication.	Block processing increases computational load and may introduce processing delay.	121

2.8.1.1 Convergence

Despite its robustness, low computational cost, and good tracking capability, the LMS algorithm is widely reported to suffer from slow convergence. This drawback is particularly can be seen during the initial adaptation stage when the regressor vector exhibits strong correlation among its entries [123]. The convergence speed of the LMS algorithm is influenced by the characteristics of the input signal and the selected initial conditions. When a zero initial condition is used, the convergence behavior depends on how closely the input power spectral density (PSD) signal spectrum matches the optimal Wiener solution. [124].

In [124], the authors proposed a method to accelerate the convergence rate by varying the length of the adaptive filter. A larger step size was applied when a shorter filter was used to achieve faster convergence. Although this approach successfully improved convergence performance, it resulted in increased computational complexity. A practical approach to address this issue has been suggested by adding one or two sub-filters at each stage to reduce the overall computational cost. The authors also stated that dynamically switching between stages or allowing the filter to revert to a previous stage were identified as potential directions for future work.

Over the years, the advancement of technology has intensified environmental noise issues, motivating the development of various adaptive algorithms for noise cancellation. Agarwal in [125] proposed the implementation of several adaptive

algorithms and compared their performance in noise cancellation applications. The study evaluated performance in terms of mean square error (MSE), noise reduction capability, computational complexity, and stability. The results indicated that while the RLS algorithm achieved the fastest convergence, it also came with high computational complexity and significant memory requirements.

Authors in [126] introduced Order Statistic Normalized Average Least Mean Square (OS-NALMS) algorithm with a variable step size for frequency-domain equalization. The performance of the proposed method was evaluated through simulations in terms of bit error rate (BER), mean square error (MSE), and convergence speed. Its effectiveness was demonstrated by comparing it with the conventional OS-NALMS algorithm that employs a fixed step size. In addition, the proposed method was tested using different filter tap lengths and under zero-forcing (ZF) equalization. The results showed that the variable step-size OS-NALMS achieved acceptable performance and compared favorably with existing ZF equalization methods.

Authors in this research designed adaptive channel equalization algorithms for FBMC systems with offset QAM modulation (OQAM) [127]. Because of its simplicity, LMS-based adaptive equalizer was employed to minimize the mean square error (MSE). A per-subchannel fractionally spaced (T/2) equalizer was used to reduce aliasing effects between subchannels. The study further examined the convergence behavior and computational complexity of the LMS equalization scheme under different step sizes and numbers of subcarriers using the ITU VEH-A channel model. Simulation results indicated that due to channel frequency selectivity each subchannel requires a different optimal LMS step size depending on its correlation characteristics. However, this requirement for individually optimized step sizes limits the practicality of LMS equalization in highly dynamic channel environments.

This research addressed the interference and noise challenges in FBMC-QAM systems by proposing an adaptive channel equalization based on a dynamic step-size LMS algorithm [128]. The proposed method aimed to improve convergence speed and enhance error stability compared to the conventional LMS approach by applying a sigmoid function and additional control parameters. Theoretical analysis and simulation results showed that the dynamic step-size LMS achieved faster convergence and lower error levels, leading to improved BER performance when compared with both the standard LMS algorithm and a residual deep neural network (Res-DNN) equalization method. However, the introduction of additional parameters may limit its practicality in

low complexity implementations.

Ensuring its applicability in next generation wireless system, authors in [129] introduced a novel self-interference cancellation method based on an optimized LMS algorithm for Co-frequency Co-time Full Duplex (CCFD) systems. The proposed approach demonstrated a significant improvement in convergence speed compared with other reference algorithms, while maintaining a low steady-state error (SSE). Both theoretical analysis and simulation results showed that the algorithm achieves a good balance between fast convergence and stable error performance and exhibits effective channel tracking capability in the presence of burst noise interference. These characteristics indicate its suitability for 5G wireless communication environments. However, the evaluation was conducted under ideal simulation conditions, and nonlinear interference effects were not considered.

Finding	Limitation	Reference
Variable-length LMS improves the initial convergence of adaptive filters.	Changing the filter length adds complexity and requires parameter control.	124
Adaptive LMS filtering effectively reduces unwanted noise.	The study focuses on noise cancellation rather than channel equalization.	125
Variable-step-size order-statistic LMS improves convergence, BER and MSE.	It was developed mainly for OFDM frequency-domain equalization.	126
LMS equalization reduces channel distortion in FBMC systems.	Conventional LMS has slow convergence and depends on the selected step size.	127
Dynamic step-size LMS reduces interference in FBMC-QAM more effectively than fixed-step LMS.	Dynamic step-size calculation adds computational complexity.	128
The optimized LMS algorithm improves self-interference cancellation in full-duplex 5G systems.	It focuses on full-duplex self-interference rather than FBMC channel equalization.	129

2.8.1.2 Training Rate

In the context of LMS adaptive equalization, both the training sequence and the training rate influence the overall learning behavior of the filter, but it is the training rate that plays the dominant role in improving convergence [21]. A well-designed training sequence is necessary because it provides the correct reference symbols required to compute the instantaneous error and guide the weight updates. However,

even a perfectly constructed training sequence cannot ensure fast or stable convergence if it is transmitted only once or too infrequently.

The key factor that accelerates LMS convergence is how often these reference symbols are inserted into the data stream. A higher training rate supplies the equalizer with more frequent and reliable error information, allowing the algorithm to update its coefficients in the correct direction and respond more effectively to channel variations [130]. This frequent injection of known symbols significantly reduces misadjustment, suppresses error propagation in decision-directed mode, and improves the stability of the adaptation process, especially in fast-fading or interference-rich environments.

In OFDM systems, where the cyclic prefix simplifies the channel and reduces intersymbol interference, the training rate can remain relatively low. In contrast, FBMC suffers from intrinsic interference due to the absence of a CP and overlapping OQAM symbols, making the system more sensitive to incorrect updates and requiring a higher training rate to maintain reliable convergence [131]. Thus, while the training sequence is essential for initializing and maintaining the adaptation, it is the training rate that fundamentally determines how quickly and accurately the LMS algorithm converges.

As stated by author in [132], this technique will also help step size to control convergence of LMS algorithm. For the mitigation of ISI, the authors in [11] applied periodic training pattern in a high speed adaptive linear equalizer. The ISI was evaluated using level detection after applying the training pattern, and the results confirmed that interference was reduced in the linear equalizer based on the observed level differences. However, this approach has a drawback. Its effectiveness is limited by high computational complexity, as the equalizer cannot efficiently process large sequences simultaneously.

The authors in [133] applied training sequences with an RLS algorithm to estimate channel state information in OFDM systems. The same training-based approach was employed across all OFDM blocks to reduce the overall computational complexity of the RLS algorithm. The transmitted signal consisted of both information symbols and training sequences, with matrix inversion performed before the training phase to limit computational overhead. Although this method improved the mean square error (MSE) performance of channel estimation however the use of training sequences consumed additional time slots thereby reducing transmission rate and spectral efficiency.

Authors in [134] proposed a time and frequency synchronization technique for

MIMO-OFDM systems based on training sequences. The proposed scheme was designed to operate effectively in both burst and continuous transmission modes while maintaining reliable performance. Preventing performance degradation in correlation between transmitted and received training sequences, frequency offset estimation using the cyclic prefix (CP) was performed before time synchronization. Simulation results shows that the method achieved good synchronization performance even at low SNR levels and in frequency-selective channels. However, the training sequence cannot be directly modulated in the time domain because Fourier transform does not exhibit constant magnitude

Another approach using training rate has been proposed by authors in research [130]. This work addressed ISI in high symbol rate intensity modulation and direct detection (IM/DD) systems by proposing a novel training sequence to improve LMS-based channel equalization. A first-order Markov chain was used to generate correlated training symbols, shaping the signal spectrum to accelerate convergence compared with conventional method. Both simulation and experimental results demonstrated faster convergence and reduced mean square error, enabling a significant reduction in the required training length. Experimental validation with high-speed PAM-4 transmission showed improved BER performance while achieving substantial training length reduction. However, the evaluation was limited to a fixed modulation format and the impact of higher modulation orders on training rate reduction was not discussed.

Many LMS based methods have been developed to improve convergence speed and reduce training needs but they may not work well in complex channel conditions [135]. RLS as one of the adaptive algorithm that require more computation. This algorithms are often used because they can adapt more quickly and track changes better.

Finding	Limitation	Reference
The adaptive linear equalizer detects the ISI level and adjusts equalization for high-speed transmission.	It requires a periodic training pattern and was tested for a wired communication channel.	11
The correlated training sequence accelerates LMS convergence and reduces the required training length.	It is designed for optical IM/DD systems rather than wireless FBMC systems.	130
The adaptive space-time scheme improves wireless communication performance under changing channel conditions.	The adaptive processing increases system complexity and requires channel information.	132
RLS with superimposed training improves OFDM channel-estimation accuracy and reduces training overhead.	RLS requires high computational complexity and the superimposed data can interfere with channel estimation.	133
The proposed synchronization method estimates timing and frequency offsets in MIMO-OFDM systems.	It focuses on OFDM and requires additional synchronization and training processing.	134

2.8.2 Recursive Least Square (RLS)

The RLS algorithm is an adaptive filtering technique that offers significantly faster convergence and more accurate tracking. RLS updates the equalizer coefficients by minimizing the exponentially weighted least-squares error, enabling rapid adaptation even in rapidly time-varying and highly frequency-selective channels. In OFDM systems, RLS-based equalizers provide improved resistance to Doppler spread, phase noise making them suitable for high-mobility scenarios where LMS cannot track channel variations effectively. RLS also achieves lower steady-state error, allowing more reliable subcarrier equalization in low-SNR or severely fading conditions.

Despite its superior performance, RLS comes with notable drawbacks. Although RLS is also one of the adaptive algorithm commonly used due to its fast convergence, but this benefit comes at the cost of high computational complexity [122]. The reason is because it involves matrix updates and inversions per iteration, which can become a disadvantage in multicarrier systems with large equalizer lengths. RLS is also more sensitive to numerical stability issues, requiring careful tuning of the forgetting factor and regularization parameters.

Furthermore, the algorithm can be unstable in low-noise environments or when the input signal is poorly conditioned. These limitations become even more critical in

FBMC systems, where the overlapping nature of prototype filters and intrinsic interference introduce stronger symbol correlation than in OFDM, demanding careful algorithm configuration to avoid numerical divergence. When combined with DFE, RLS provides faster and more precise adaptation of both the feedforward and feedback filters compared to LMS. This makes RLS-DFE highly effective in channels with strong ISI, where rapid coefficient updates are essential for preventing error buildup.

In OFDM, RLS-DFE has been used to mitigate residual ISI in severely dispersive channels or when CP length is insufficient. In FBMC, RLS-DFE becomes even more advantageous because the nonlinear feedback structure helps suppress the intrinsic interference generated by OQAM staggering and long filter overlap. The fast convergence of RLS ensures that the DFE can adapt quickly to the tighter symbol coupling inherent in FBMC. The error propagation remains a concern due to the decision-directed nature of DFE. However, its higher complexity and sensitivity to numerical instability require careful consideration, especially in advanced architectures such as MIMO-FS-FBMC where computational load and interference interactions are more demanding.

Authors in [136] introduce a new method by combining RLS and LMS based on the error threshold. RLS helped the system switch to LMS if the error signal is less than errors threshold. Although the results proved the efficiency of this proposed method, it only tested in the OFDM system. The Dual Kalman Filter method with FBMC was proposed by authors in [137]. The authors compared the results with conventional LMS and RLS algorithms. Their proposed method succeeds in outperforming both adaptive algorithms. However, the author's research did not cover the MIMO operation and was also limited to synthesis polyphase filter.

The RLS equation can be written as [24],

$$w(k) = w(k-1) + G(k)e(k) \tag{2.12}$$

G(k) is the gain vector, e(k) is the a priori error, and w(k) is the updated equalizer coefficient vector

$$G(k) = \frac{P(k) \cdot R(k)}{\lambda + R^T \cdot P(k) \cdot R(k)} \tag{2.13}$$

λ is a forgetting factor with a value between 0 and 1. A smaller λ allows faster convergence but if it is too small the algorithm may become unstable. P(k) represents the inverse correlation matrix, R(k) is input signal vector while R^T is real signal transpose. R^T will become R^H when added to complex signals.

2.8.2.1 Matrix Inversion

The RLS algorithm is widely recognized for its fast convergence and superior mean-square error (MSE) performance compared to gradient-based algorithms such as LMS. However, the efficiency of RLS relies heavily on the continuous estimation of the inverse autocorrelation matrix, usually denoted as $\mathrm{P}(k) = \mathrm{R}^{-1}(k)$. In classical least-squares estimation, computing the Wiener solution requires solving a linear system $\mathrm{Rw} = \mathrm{p}$, which involves an explicit matrix inversion with cubic computational complexity $O(M^3)$ [123]. It becomes prohibitive in multicarrier systems like OFDM and FBMC, especially when large filter lengths or frequency-selective channels are considered. RLS avoids direct inversion by using the Matrix Inversion Lemma to update $\mathrm{P}(k)$ recursively using only matrix–vector multiplications. This drastically reduces the cost to $O(M^2)$per iteration. In FBMC systems, where the absence of cyclic prefix results in higher intrinsic interference, RLS benefits strongly from efficient inversion because it must track rapidly changing correlation structures across overlapping subcarriers. Overall, matrix-inversion-driven RLS remains a dominant adaptive equalization approach for OFDM/FBMC due to the balance it offers between tracking capability, precision, and computational feasibility.

An iterative approach for computing the inverse matrix was first introduced by this author in his book and later implemented on Field Programmable Gate Arrays (FPGAs) [138]. Several years afterward, this work was extended through a new adaptive predistortion method based on LMS and RLS algorithms for OFDM systems [136]. The proposed method showed good robustness when large error signals were present and was able to maintain stable convergence. However, despite these positive results the RLS may still experience occasional modulation errors, which can lead to unexpected performance issues in certain scenarios. Both of these research papers mentioned advantages of matrix inversion in their system [139][140]. The authors also concluded that matrix inversion technique can improve the performance of the filter.

Instead of using direct matrix inversion, the authors in [141] reformulate the

inverse matrix update using tensorial forms. This approach breaks the large inverse matrix into smaller and more manageable components, allowing the RLS algorithm to update the inverse information using simpler operations. The proposed method maintains stable convergence and achieves performance close to conventional RLS while requiring fewer multiplications and less memory. By simplifying how the inverse matrix is handled, the algorithm becomes more suitable for real-time and hardware implementations.

Finding	Limitation	Reference
Combining RLS and LMS improves digital predistortion for nonlinear OFDM power amplifiers.	It focuses on amplifier linearization rather than channel equalization.	136
Dual Kalman filters improve channel estimation and BER in time-varying FBMC/OQAM channels.	The method requires pilot symbols and channel-model estimation.	137
FPGA implementation provides high-speed and flexible digital signal processing.	Hardware design requires FPGA resources and implementation knowledge.	138
Sparse kernel RLS improves nonlinear system identification while controlling model size.	Kernel processing still requires additional computation and parameter selection.	139
Power normalization improves SINR, spectral efficiency and energy efficiency in massive MIMO beamforming.	It focuses on beamforming power allocation rather than FBMC equalization.	140
Tensor-based RLS reduces computational complexity while maintaining good estimation performance.	It is mainly evaluated for multilinear system identification.	141

2.9 Adaptive Equalizer

Adaptive equalizers use adaptive algorithms to converge to the true coefficients and have the benefit of tracking changes in channel impulse response [119]. This type of equalizer widely employed in modern wireless communication systems to mitigate intersymbol interference (ISI) and maintain reliable symbol detection in time-varying, frequency-selective channels [117]. Depending on their structure, adaptive equalizers are commonly categorized into linear and non-linear types. Linear adaptive equalizers, such as the transversal FIR equalizer, estimate transmitted symbols using a linear combination of received samples and are well-suited for scenarios with moderate ISI and stable channel conditions.

Classical linear equalizers include the Zero-Forcing (ZF) equalizer and the Minimum Mean Square Error (MMSE) equalizer. The ZF method completely removes ISI by inverting the channel response but can significantly amplify noise in deep fades, while the MMSE equalizer achieves a balanced trade-off between noise enhancement and ISI suppression, making it more robust under practical multipath fading environments [142]. Beyond these, frequency-domain equalizers (FDE) and subcarrier-wise linear equalizers are also widely applied in multicarrier systems due to their lower complexity. However, when the channel distortion becomes severe or when the equalizer must deal with higher-order interference terms, purely linear designs may not be sufficient.

Addressing such limitations, non-linear adaptive equalizers including decision feedback equalizers (DFE), Volterra-series-based equalizers, kernel-based equalizers was introduced. Non-linear decision feedback structures to cancel both precursor and post-cursor interference more effectively. These designs are especially valuable for channels with strong dispersion or non-linear fading behavior. In advanced multicarrier systems such as OFDM, F-OFDM, FBMC, and particularly frequency-spreading FBMC (FS-FBMC), both linear and non-linear adaptive equalizers play critical roles due to the absence of a CP, overlapping subcarrier structure, and intrinsic interference caused by OQAM modulation [143]. In MIMO environments with STBC, adaptive equalizers further support spatial stream separation and residual interference suppression after decoding. For FS-FBMC systems, these equalizers are essential to fully exploit the frequency-spreading structure, maintain subcarrier orthogonality, and improve BER performance under complex MIMO channel conditions. Overall, current

research trends show a shift toward flexible, interference-aware, and structurally adaptive equalizer designs that can meet the robustness requirements of next-generation multicarrier systems.

2.9.1 Linear Equalizer

Linear Equalization (LE) is one of the commonly adopted receiver techniques in FBMC systems due to its simplicity and relatively low computational complexity. In FBMC, the absence of a cyclic prefix and the use of well-localized prototype filters introduce intrinsic interference between adjacent subcarriers and symbols, making equalization more challenging compared to conventional OFDM. Among LE techniques, Zero-Forcing (ZF), Minimum Mean Square Error (MMSE), and Single-Tap Equalization are the most widely used. ZF aims to completely invert the channel response, effectively removing intersymbol interference but at the cost of significant noise enhancement, especially in deep fade conditions [144]. MMSE suppresses interference and noise amplification by incorporating noise statistics, leading to improved performance of SNR [68]. Single-tap equalization represents the simplest form of LE because each subcarrier is equalized independently using a complex gain [47].

Authors in [145] investigated the impact of doubly dispersive channels for FBMC system, where both delay spread and Doppler spread are present. Their study shows that although FBMC offers excellent spectral localization and high spectral efficiency, its performance degrades significantly in time-varying channels. The reason is due to the Doppler-induced channel variations that destroy subcarrier orthogonality and lead to increase of ICI and ISI that cannot be effectively mitigated using conventional single-tap linear equalization. The authors highlight that while FBMC remains attractive for spectrally efficient communications, however reliable operation in doubly dispersive channels requires more advanced equalization techniques.

This research by authors in [30] emphasizes the effectiveness of linear equalization in enabling QAM-based FBMC (QAM-FBMC) systems to support MIMO transmission with performance comparable to CP-OFDM. Despite common belief that FBMC systems need nonlinear equalizers to support MIMO antenna, a well-designed linear receiver can also function well when QAM-FBMC is used. By investigating a two-transmit-antenna MISO STBC configuration, the study shows that the use of a

finer-resolution linear equalizer allows QAM-FBMC to achieve near CP-OFDM error-rate performance while maintaining significantly low receiver complexity.

Authors in [146] present a detailed comparison between linear MMSE equalization (MMSE-LE) and widely linear MMSE equalization (MMSE-WLE) in FBMC-OQAM systems by focusing on their BER performance characteristics. An equivalent FBMC model based on M-ary pulse amplitude modulation (M-PAM) is first derived to simplify analysis, enabling closed-form BER expressions that closely match simulation results. Conventional linear equalization in FBMC-OQAM systems is very sensitive to interference from neighboring subcarriers, whereas widely linear equalization achieves better BER performance by also using the signal's complex conjugate. However, when two adjacent subcarriers are active, both LE and WLE experience unavoidable ICI. The authors stated that widely linear equalization offers a more robust solution, albeit with increased complexity.

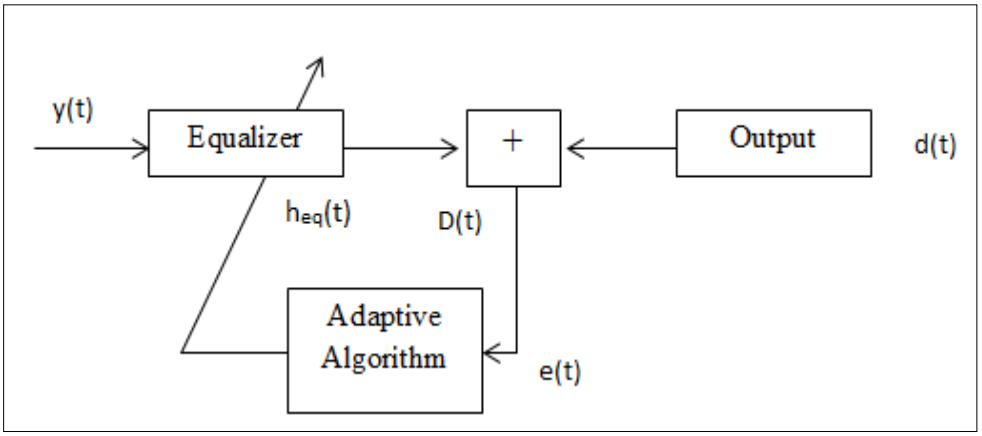

Figure 2.6 Linear Equalizer Process

Figure 2.6 above shows the process of how linear equalizer executes the received signal [147]. For Zero Forcing the equation can be described as [112] ;

$$W_k = \frac{1}{H_k} \tag{2.14}$$

For MMSE equalization, the equation can be simplify as [148];

$$W_k = \frac{H^*{}_k}{|H_k|^2\sigma^2} \tag{2.15}$$

W_k is weight equalizer coefficient, H_k is chanel frequency response and σ^2 is noise variance [112].

2.9.2 Decision Feedback Equalizer

Although MIMO-FBMC proves that it can enhance wireless communication performance, further study is required to verify its reliability and its capability to achieve the maximum diversity order. Therefore, a system with equalizer is required to improve the behavior of the system. The purpose of equalizer is to recover distorted transmit symbols. DFE is an adaptive nonlinear equalizer that used previous detector decisions to eliminate ISI on pulses that are currently being modulated. If the previous symbol's detected are known, ISI from these symbols can be cancelled out by having suitable weighting to subtract past symbols values.

DFE is also known as an upgraded linear equalizer due to its low noise enhancement [119]. Error propagation is a major problem in DFE because the design is based on the assumption that detector decisions are correct. The presence of noise in a real environment made the decision cannot always be correct. Burst of error can appear in future symbol decisions due to the presence of a feedback loop that contains current decisions with an error [149]. In 2018, Fhima and Chang compared BER performance of linear and widely linear equalizer towards the FBMC system [146]. Their outcome mentioned that equalizer can help in eliminating ISI and ICI. However, their research only applicable to indoor and flat fading environments.

In [142], the authors proposed a novel MMSE joint feedback feed-forward filter for the FBMC system. The research applied MMSE during feed-forward filter operation and also used zero forcing equalizer with the feedback filter. The results disclosed that the proposed method successfully reduced interference and also boost data rate transmission. But the author's method cost them high power consumption and temperature which can affect hardware implementation. Authors in [150] proposed a filter based on the MMSE criterion with an enhanced DFE system. Performance of BER slightly improved compared to the existing equalizer but it came with high complexity. Currently, there is limited research that applies nonlinear equalizer for MIMO-FBMC compare to OFDM [148][151][152].

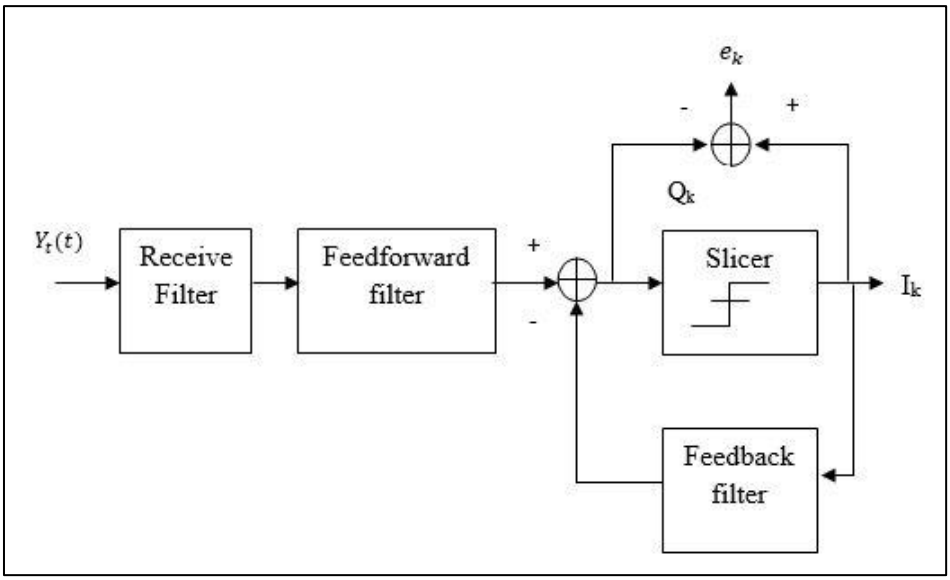

Figure 2.7 Block Diagram Of The DFE

Figure 2.7 above shows the block diagram of decision feedback equalizer (DFE) as one of the adaptive equalizers [152]. DFE utilizes a feed-forward and feed-back filter. The forward and feed-back weights can be simultaneously adjusted [149]. $Y_t(t)$ is the channel output which contains AWGN noise. This structure assumes that the equalizer is working at the symbol rate. Setting the feedback filter to zero effectively transforms the equalizer into its linear form. I_k is a training symbol used in the training period. Q_k is the decision device input. Adaptation of equalizer is done according to error signal e_k**.** Error signal equation can be written as [121];

$$e_k = I_k - Q_k \tag{2.16}$$

There can be decision errors because of the period at the initial filter or false equalizer impulse response [119].

Finding	Limitation	Reference
STBC with linear equalization improves the performance of QAM-FBMC MIMO systems.	Linear equalizers may not sufficiently remove severe ISI and ICI.	30
The MMSE feedback–feed-forward equalizer reduces ISI and ICI in 60 GHz FBMC-OQAM systems.	It requires additional feedback processing and is designed specifically for 60 GHz channels.	142
FBMC performs well under moderate doubly dispersive channels.	Large Doppler or delay spread causes severe interference and an error floor.	145
Widely linear equalization provides better BER than conventional linear	It requires more signal processing than a conventional linear equalizer.	146

equalization for FBMC-OQAM.		
The enhanced MMSE-DFE improves ISI and ICI suppression under severe multipath channels.	The additional interference-suppression filters increase computational complexity.	150

2.10 Diversity

Although the execution of FBMC with low complexity is important, diversity is also one of the main reasons to enhance the reliability of communication links. The system with multiple antennas provides spatial diversity that can be exploited with block coding. ST, SF and STF are widely used by researchers in the OFDM system but in FBMC, the study is not well developed yet [153][154].

Diversity techniques are employed to exploit multipath and reflected signals that commonly arise in non-line-of-sight (NLOS) environments. At both the transmitter and receiver, diversity plays a crucial role in reducing the impact of channel fading and preventing long bursts of errors. By combining multiple signal paths, diversity enhances the robustness and overall reliability of the transmitted information [155]. The application of MIMO in this system become one of key advantage of this research. In a typical wireless communication channel, diversity can be achieved through several approaches such as spatial diversity, temporal diversity and frequency diversity. This method will help improve signal robustness and system performance.

2.10.1 Space Time Block Code

Although FBMC has attracted strong interest for future wireless systems due to its high spectral containment but supporting MIMO is difficult because FBMC/OQAM relies on real-valued orthogonality and omits the cyclic prefix which introduces intrinsic interference. Because of this reason, conventional Alamouti STBC cannot be directly applied to FBMC systems. According to this author, the issue can be addressed by extending a block-wise Alamouti-based STBC for a 2×2 MIMO-FBMC system [156]. Simulation results show that, without additional measures, the BER performance of FBMC with this STBC is worse than that of classical Alamouti-coded OFDM. However, by inserting an empty symbol as a guard interval (GI) between Alamouti blocks, the intrinsic interference is significantly reduced, allowing the FBMC system to

achieve BER performance close to OFDM.

In 2016, Kusume and Weitkemper proposed Pulse Amplitude Modulation (PAM) Alamouti scheme with FBMC inspired by basic Alamouti code which was a prominent diversity scheme in wireless communication. The idea introduced data with symbols and a precoding symbol to adapt with FBMC orthogonality in the real domain. Despite having successfully increased the rate of transmission, the method only applicable for two transmit antennas and not suitable for the system that demands usage of more antennas [157]. Previous researchers in [30] proposed QAM-FBMC with ST for 4G-LTE and compared the performance with CP-OFDM. The results show remarkable improvement in the reduction of BER. However, the research only focused on multiple input single output (MISO) and linear equalizer.

Analysis of ST with FBMC had been studied by authors in [158]. Authors stated that most of the works had considered well known Alamouti scheme for ST FBMC such as blockwise, interference cancellation and pseudo-Alamouti. There were also a few works proposed slightly changes in the modulator or demodulator of FBMC by introducing Code Division Multiple Access (CDMA) FBMC and specific arrangement of FFT FBMC. The outputs yield notable performances, but it comes with the expense of either complexity escalation or spectral efficiency reduction. Although noteworthy ideas had been proposed to increase diversity in FBMC, researchers were focusing on the implementation of ST despite the fact of the impressive performance of STF in OFDM before.

The authors in [159] propose method by including a CDMA component into the OFDM/OQAM system, which enables the combined transmission scheme to satisfy the complex orthogonality condition required by Alamouti STBC. The study emphasizes that the design of the CDMA–OFDM/OQAM system must carefully consider the characteristics of the transmission channel. Simulation results for a 2×1 Alamouti-coded system compare CDMA–OFDM/OQAM with conventional CP-OFDM in two scenarios which were CDMA applied in the frequency domain and CDMA applied in the time domain. The results prove that with appropriate system design, Alamouti space time diversity can be supported in OFDM/OQAM system but the performance depends on how CDMA is implemented. The basic code rate for STBC can be calculated as [160];

$$R = \frac{k}{T} \tag{2.17}$$

Where k is number of symbol transmitted in one block and T is number of time slots or symbol period.

2.10.2 Space Frequency Block Code

Although Space Frequency Block Coding (SFBC) can be adapted for FBMC systems, its implementation is challenging due to the absence of complex orthogonality and the presence of intrinsic interference. Despite the challenges, modified SFBC approaches such as including guard tones, block-wise mapping, or advanced receiver processing can be considered. However, these solutions increase system complexity and reduce spectral efficiency. Author in [161] proposed OQAM/FBMC with SFBC MIMO. The idea was to integrate SFBC on a complex signal before the OQAM processing. This idea is to prevent the intrinsic interference. However this method is strictly for lower orders of modulation which the author only uses 4QAM. When compared with 16 QAM, the system has no significant gain over conventional OQAM/FBMC. Research regarding SFBC in FBMC is very limited. Although space frequency is well known in other multicarrier modulation however in FMBC, time-domain Space–Time Block Coding (STBC) is generally favored over SFBC.

2.10.3 Space Time Frequency Block Code

Space–Time–Frequency Block Coding (STFBC) can be applied in FBMC systems using block-wise or real-valued coding schemes, often combined with guard intervals or advanced receiver techniques. While STFBC provides significant diversity gains, it also increases system complexity and reduces spectral efficiency. As a result, STFBC in FBMC is largely of theoretical interest, whereas time-domain Space–Time Block Coding (STBC) remains the most practical approach to achieve diversity.

Finding	Limitation	Reference
The Alamouti scheme improves diversity and BER in 2 × 2 MIMO-FBMC systems.	Intrinsic FBMC interference affects Alamouti orthogonality and requires additional processing.	156
The proposed orthogonal design enables full transmit diversity in FBMC-OQAM.	Precoding and interference-cancellation processes increase system complexity.	157
Space-time coding improves the reliability of FBMC systems through spatial diversity.	Guard symbols or interference cancellation may be required, reducing efficiency.	158
CDMA spreading enables the Alamouti scheme to be applied to OFDM-OQAM.	The spreading process adds complexity and may reduce spectral efficiency.	159
The hybrid OQAM-FBMC MIMO structure improves MIMO compatibility and system performance.	The hybrid structure requires additional transmitter and receiver processing.	161

2.11 Summary

In summary, the reviewed literature highlights that multicarrier systems such as FBMC have gained significant attention as alternatives to conventional OFDM due to their improved spectral efficiency and better performance in frequency-selective channels. However, existing studies largely focus on isolated performance aspects including PAPR reduction, computational complexity mitigation or BER enhancement through advanced equalization and diversity techniques. Complexity reduction techniques such as efficient complex multiplication structures and adaptive filtering optimizations have been investigated, yet their direct impact on overall system reliability is not consistently addressed in an integrated framework. On the receiver side, adaptive equalization methods such as LMS and RLS have been widely applied to mitigate ISI in multicarrier systems. While LMS offers lower complexity, it suffers from slow convergence whereas RLS provides faster adaptation at the expense of higher computational cost. Nevertheless, the majority of published works evaluate these techniques independently rather than as part of a unified system design. Therefore, extensive research is required to develop a comprehensive MIMO FS-FBMC framework that jointly addresses PAPR reduction, computational complexity optimization and BER improvement using practical and low-complexity approaches.

CHAPTER 3
RESEARCH METHODOLOGY

3.1 Introduction

This chapter explains the complete methodological framework employed to design, implement, and evaluate the proposed MIMO-FS-FBMC communication system enhanced with Space Time Block Coding (STBC), Joint Optimization Scheme (JOS), Additional Multiplication Method (AMM), Enhanced Cascaded Least Squares (ECLS) equalization, and an upgraded hybrid LMS–RLS adaptive algorithm. The methodology aims to form a systematic workflow that accurately reflects the signal processing stages of a practical multicarrier system while enabling rigorous performance evaluation in terms of BER, PAPR, computational complexity and robustness against ISI/ICI. The chapter begins by describing the overall system architecture, including the generation of QAM symbols, OQAM preprocessing, frequency-spreading filtering, MIMO mapping, and the integration of the Alamouti STBC encoder. The modelling of the wireless propagation channel including multipath Rayleigh fading and AWGN is also detailed to ensure realistic simulation conditions. Following this, the complete FS-FBMC transmitter and receiver structures are presented, emphasising the role of frequency spreading to improve spectral containment and to avoid the need for a cyclic prefix.

3.2 Research Flowchart

This section briefly describes the research methodology and the overall workflow adopted in this study. Figure 3.1 shows the methodology workflow adopted in this research. In the proposed MIMO FS-FBMC system, JOS and AMM are integrated at the transmitter to improve PAPR and complexity while ECLS is introduced at the receiver to enhance equalization performance.

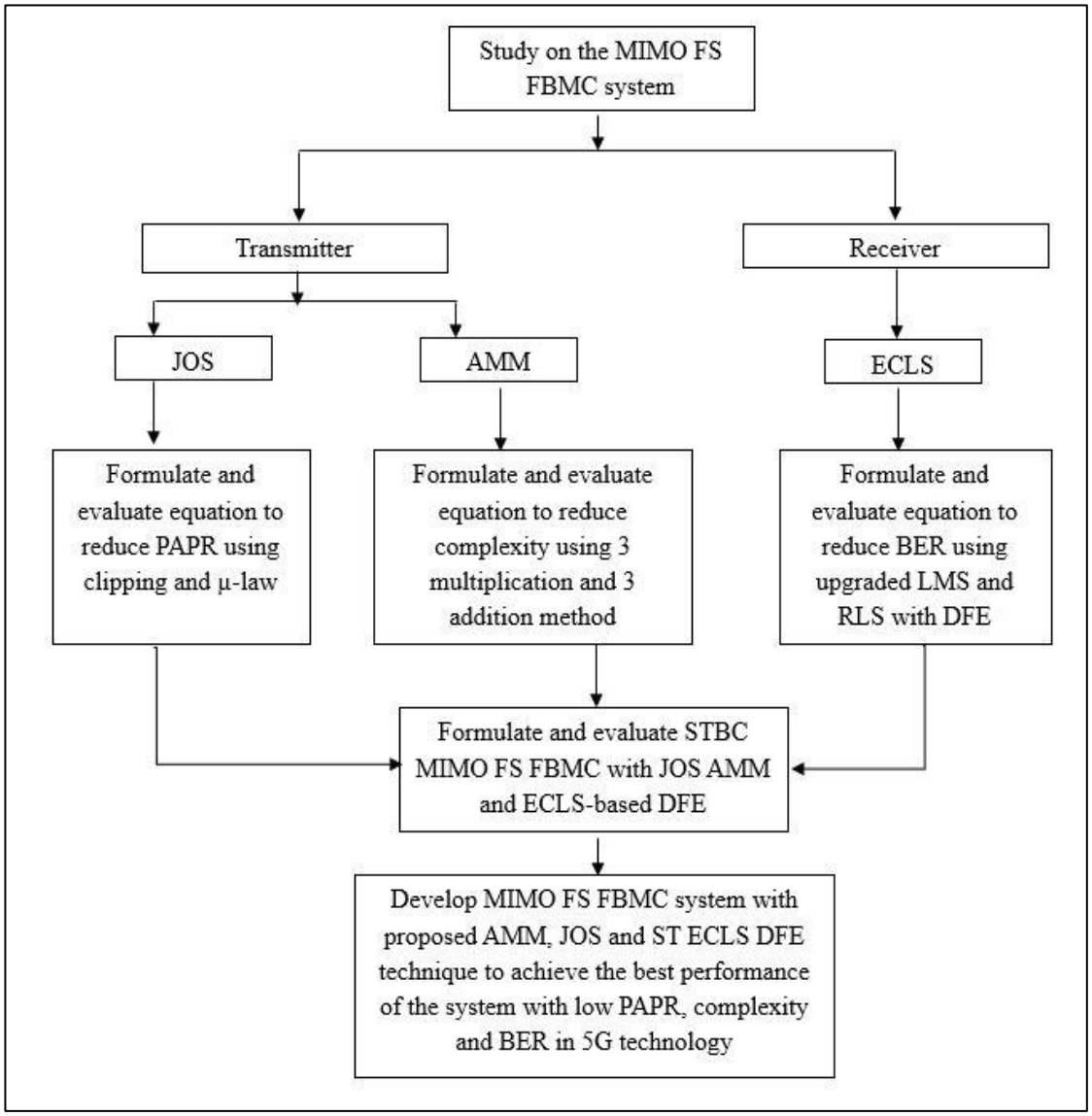

Figure 3.1 Methodology Of The Research Work

The "Formulate Equation" stage refers to the systematic development of the mathematical expressions representing each block and algorithm in the proposed MIMO FS-FBMC system. The "Evaluate Equation" stage refers to the implementation of the formulated equations through MATLAB simulations.

3.3 System Model

This section presents the system model of the proposed FBMC OQAM-based transmission scheme incorporating space time diversity and adaptive signal processing techniques. The objective of the proposed model is to enhance transmission reliability and spectral efficiency while mitigating the effects of multipath fading, noise, and nonlinear distortions. Based on the Figure 3.2 below, the overall system is divided into three main parts: the transmitter, the wireless channel and the receiver.

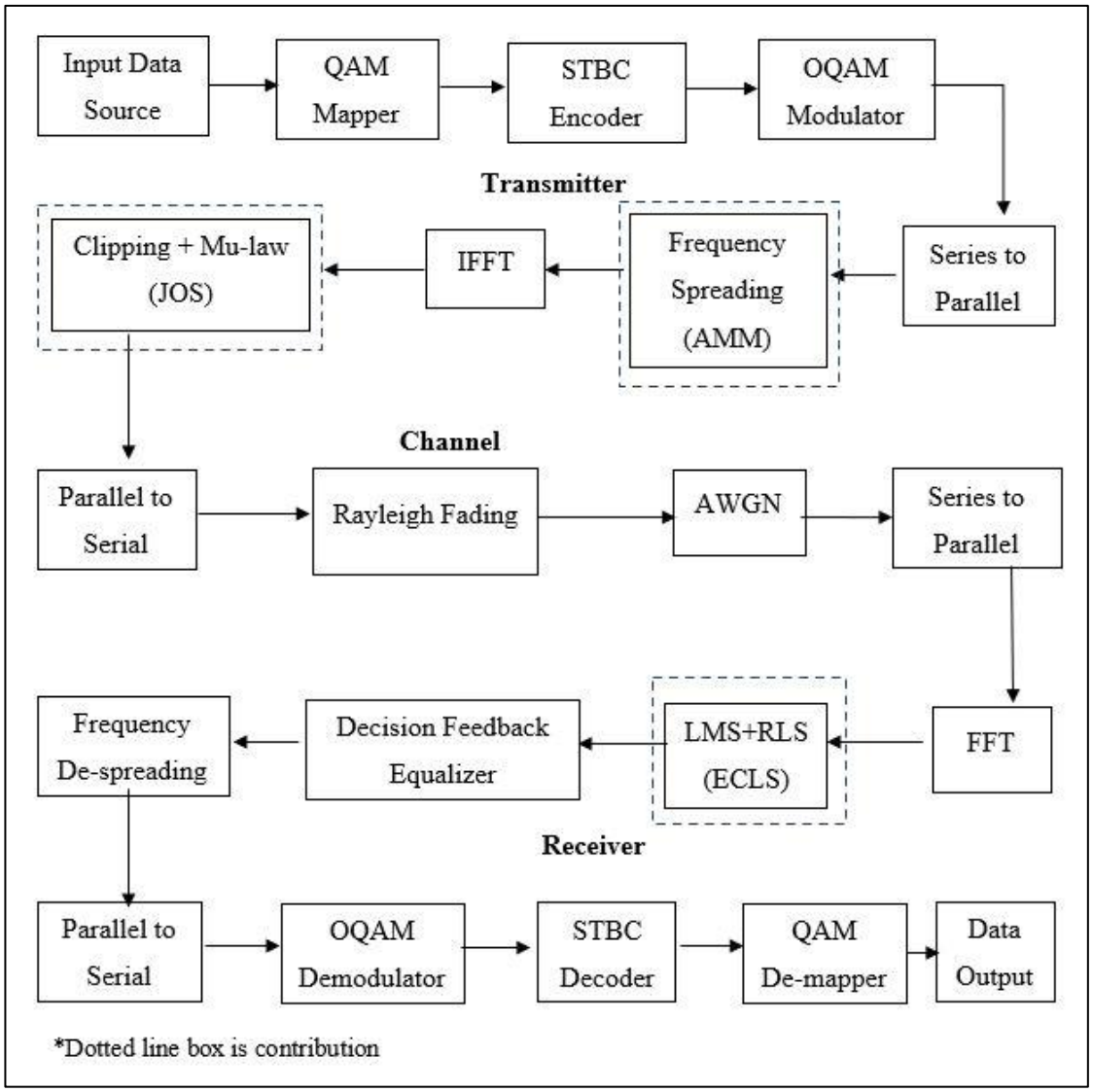

Figure 3.2 System Model Block Diagram (Overall)

Figure 3.3 below illustrate transmitter part with AMM and JOS proposed for this research.

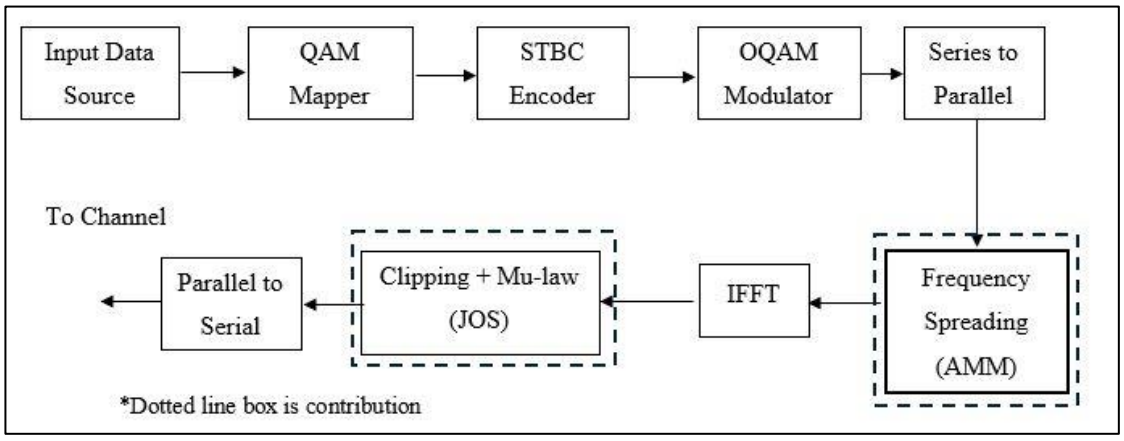

Figure 3.3 Transmitter Section

The proposed transmitter architecture for the MIMO FS-FBMC system begins with a binary input data source where random bits are generated and organized into symbol blocks according to the selected modulation order. These bits are first mapped into complex constellation symbols using Quadrature Amplitude Modulation (QAM), where the modulation order determines the trade-off between spectral efficiency and error performance. The QAM symbols are then processed by a Space-Time Block Coding (STBC) encoder to introduce spatial diversity across multiple transmit antennas. In the proposed configuration the STBC encoder distributes the symbols over four transmit antennas and multiple time slots to enhance reliability under fading channel conditions. After STBC encoding, the symbols are converted into Offset-QAM (OQAM) format, where the real and imaginary components are staggered by half a symbol duration to satisfy the real orthogonality condition required in FBMC systems.

After OQAM processing, the serial data stream is converted into parallel subcarrier streams for multicarrier transmission. To reduce computational complexity during this operation, the Additional Multiplication Method (AMM) is incorporated by optimizing matrix computations and minimizing redundant multiplications without degrading signal quality. The processed signal then undergoes frequency spreading, which is the core principle of Frequency-Spreading FBMC (FS-FBMC). In this stage, each subcarrier is spread across frequency bins using prototype filter coefficients to enhance spectral containment.

Subsequently, Inverse Fast Fourier Transform (IFFT) converts the frequency-domain signal into the time domain by combining all subcarriers into a composite multicarrier waveform. Unlike conventional OFDM systems, no cyclic prefix is added

which means preserving spectral efficiency. In order to address the high Peak-to-Average Power Ratio (PAPR) issue, a hybrid clipping and μ-law companding technique is applied. The clipping stage limits excessive signal peaks while μ-law companding smoothly compresses high amplitudes to reduce nonlinear distortion system efficiency. Finally, the parallel time-domain samples are converted back into a serial stream for transmission over multiple antennas.

Figure 3.4 below shows receiver part of the system which contains proposed ECLS method.

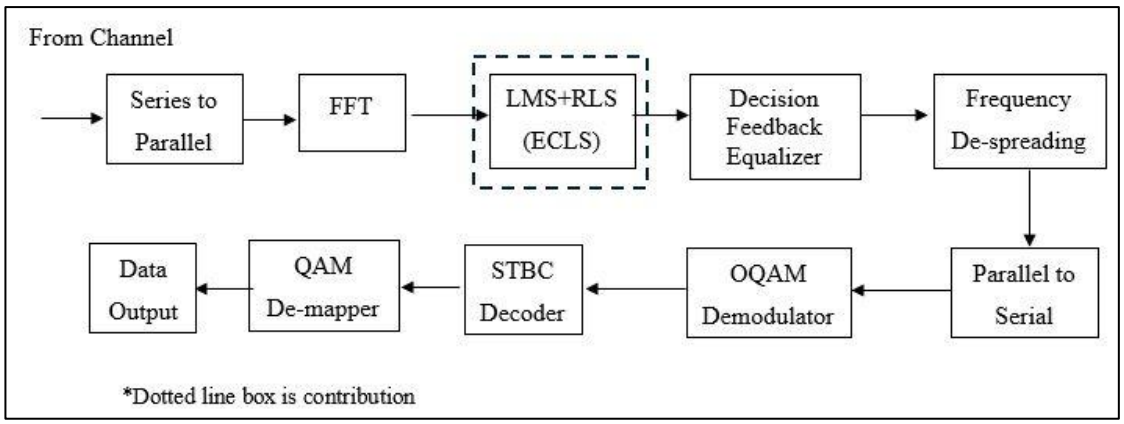

Figure 3.4 Receiver Section

The receiver process begins when the transmitted signal propagates through the wireless channel. During this process, the signal is affected by noise, fading, and multipath interference. The received time-domain signal from each antenna is first converted from serial to parallel format to prepare it for multicarrier processing. This operation organizes the incoming samples into blocks corresponding to the FFT size. An FFT operation is then performed to transform the signal from the time domain into the frequency domain, separating the individual subcarriers. This step recovers the multicarrier structure introduced by the IFFT at the transmitter and enables frequency-domain equalization and interference mitigation.

Following the FFT stage, the signal is processed by the cascaded adaptive equalization structure consisting of LMS and RLS algorithms, integrated with a Decision Feedback Equalizer (DFE). The LMS algorithm provides stable adaptation with relatively low complexity while the RLS algorithm offers faster convergence through recursive coefficient updates involving matrix inversion. By cascading LMS with RLS the receiver benefits from both fast tracking capability and reduced steady-state error. The DFE further enhances performance by canceling post-cursor inter-

symbol interference (ISI) using previously detected symbols in a feedback loop. This combined equalization structure significantly improves BER performance in frequency-selective and fading channels.

After adaptive equalization, the signal proceeds to the frequency despreading stage, which is the inverse operation of frequency spreading in the FS-FBMC transmitter. Here, prototype filter coefficients are applied in the frequency domain to recombine the spread subcarrier components and restore the original subcarrier symbols. The processed parallel data is first converted back into serial format before undergoing OQAM demodulation, where the staggered real and imaginary components are recombined to reconstruct the complex QAM symbols. These reconstructed symbols are then passed to the Space Time Block Coding (STBC) decoder which combines the received signals from multiple antennas to exploit spatial diversity and recover the transmitted symbols under fading conditions. After STBC decoding, the estimated QAM symbols are forwarded to the QAM demapper, which converts the constellation points back into binary bits according to the corresponding decision boundaries. Finally, the recovered bits are delivered as the output data indicating the completion of the receiver processing chain.

STBC was selected to improve diversity and BER while FS was chosen over PPN because its frequency-domain structure allows easier integration of the proposed AMM algorithm [162]. Rayleigh fading was used to represent a non-line-of-sight multipath channel and 16-QAM with OQAM processing was selected to balance spectral efficiency and error performance [163][164].

3.4 System Parameter

The simulation parameter shown in Table 3.1 are selected in accordance with the high data rate millimeter-wave framework with necessary adaptation to support FBMC based transmission structure.

Table 3.1
System Parameter Simulation[165]

Parameter	Values
FFT size	2048
Number of Subcarriers	2048
Modulation Technique	16 OQAM
Channel	COST 207 TU
Overlapping factor [166]	4
Number of filters [167]	4

Referring to table above, FFT size of 2048 is employed with all 2048 subcarriers actively utilized. This large FFT dimension provides fine frequency resolution and enables high spectral efficiency which is suitable for broadband wireless applications operating at gigabit data rates. By allocating all subcarriers for data transmission, the system maximizes bandwidth utilization. At the same time, this process allows detailed observation of the behaviour of interference and equalization in the FS-FBMC framework.

A 16-OQAM modulation scheme is used for FBMC-OQAM transmission signalling which real-valued symbols are time staggered to preserve orthogonality without requiring a cyclic prefix. The use of 16-OQAM offers a balanced trade-off between spectral efficiency and error performance making it appropriate for evaluating BER performance under realistic channel conditions. The channel model selected is the 207-TU (Typical Urban) model which represents a multipath propagation environment with significant delay spread. This channel introduces frequency selectivity and inter-symbol interference by providing a practical scenario to evaluate the effectiveness of the proposed hybrid LMS-RLS equalizer and DFE structure.

For the FBMC structure, an overlapping factor K=4 is applied along with 4 prototype filter coefficients which determine the time-frequency localization of the subcarriers. An overlapping factor of 4 implies that each FBMC symbol overlaps with four adjacent symbols in time improving spectral containment and reducing out-of-band emissions compared to conventional OFDM. This configuration enhances spectral efficiency but increases intrinsic interference thereby justifying the need for advanced equalization techniques at the receiver. Overall, the selected parameters of large FFT size, full subcarrier utilization, 16-OQAM modulation, 207-TU channel model, and overlapping factor of 4 provide a realistic and rigorous simulation environment to evaluate the performance, robustness, and computational efficiency of the proposed MIMO FS-FBMC system.

FBMC applied complex numbers to represent transmitted and received signals. Input signals in the form of real numbers will be converted to complex value symbols. Given QAM modulated symbol;

$$s = a + bi \tag{3.1}$$

Where a is the real part and b is the imaginary part. OQAM preprocessing and postprocessing were introduced in the system to minimize interference between subcarriers. Normal QAM modulated in-phase (I) and quadrature (Q) simultaneously while offset QAM delayed Q by half symbol period of component I. This process ensures that real and imaginary will execute separately.

In the proposed FS-FBMC system, filtering is performed using the frequency spreading technique rather than conventional time-domain polyphase filtering. The transmitted symbols are multiplied by prototype filter coefficients in the frequency domain, where each subcarrier is spread across neighboring frequency bins. This frequency-domain spreading operation forms the filter bank structure and shapes the spectral response of each subcarrier. As a result, strong spectral confinement is achieved with reduced out-of-band emissions. Enhanced frequency localization allows efficient use of bandwidth and supports multiple access capability within the allocated spectrum. After frequency spreading, the composite multicarrier signal is transformed into the time domain and transmitted over the wireless channel.

The prototype filter has overlapping factor K = 2,3,4. Frequency coefficients H can be obtained from Table 3.2 below [168];

Table 3.2
Coefficients of Prototype Filter

	K =2	**K =3**	**K = 4**
H_0	1	1	1
H_1	$\sqrt{2}/2$	0.911438	0.971960
H_2	-	0.411438	$\sqrt{2}/2$
H_3	-	-	0.235147

3.5 Simulation Flowchart

Figure 3.5 shows the simulation process of the system from the initialization takes place until end of the system process.

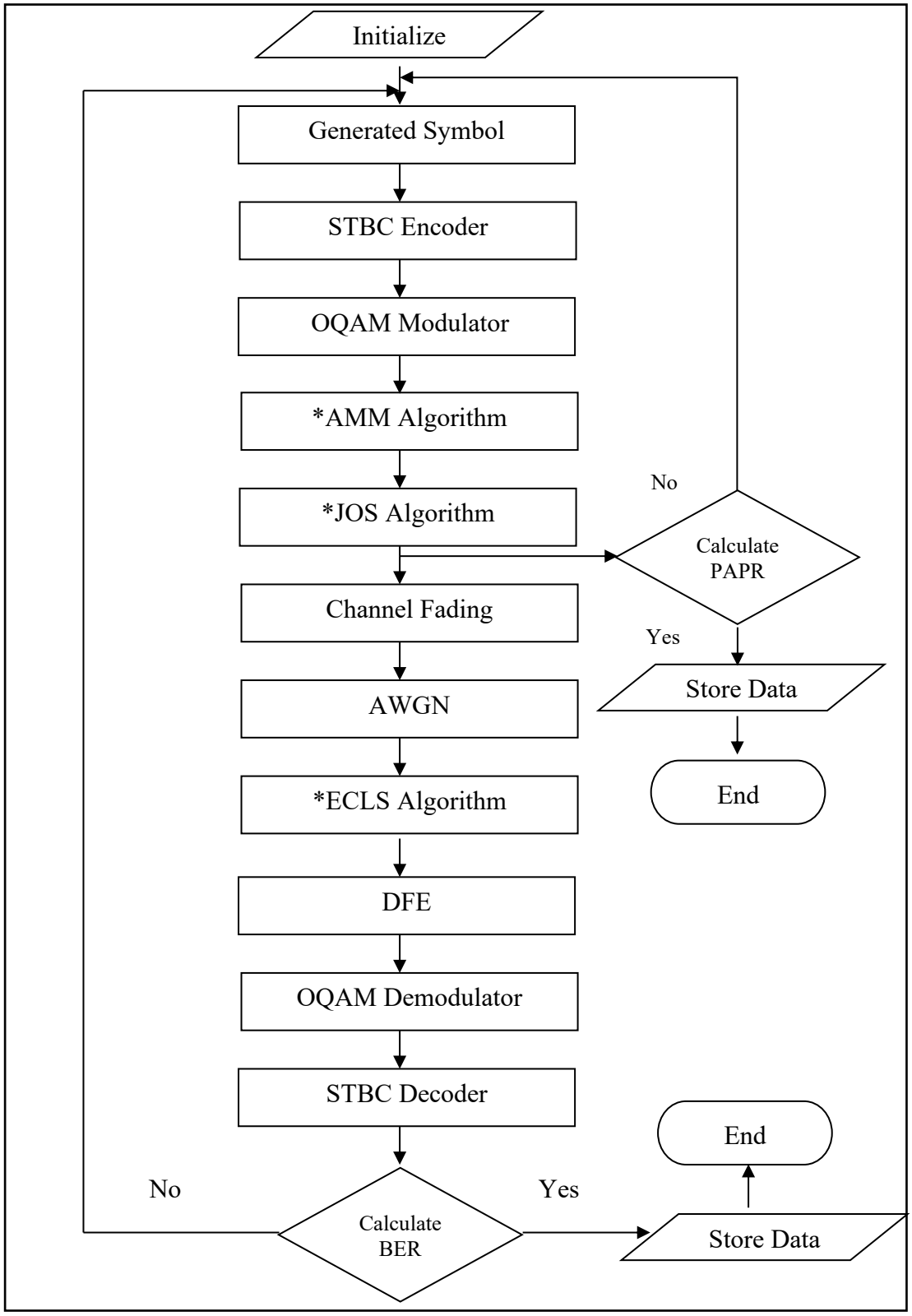

Figure 3.5 Simulation Process Of MIMO FS-FBMC

The simulation begins with system initialization, where all parameters such as FFT size (2048), number of subcarriers (2048), modulation scheme (16-OQAM), overlapping factor (K = 4), prototype filter length, channel model (207-TU), and SNR range are defined. These parameters establish the operating environment for the MIMO FS-FBMC system and ensure consistency throughout the performance evaluation.

Next, random bits are generated to represent the transmitted data and are mapped into complex symbols according to the selected QAM modulation order. These QAM symbols are then encoded using the Space-Time Block Coding (STBC) encoder to introduce spatial diversity across multiple transmit antennas. The encoded symbols are subsequently passed to the OQAM modulator, where the complex QAM symbols are converted into Offset-QAM format by staggering the real and imaginary components in time by half a symbol duration. This operation ensures real-domain orthogonality which is essential for FBMC transmission without applying cyclic prefix in the system.

After OQAM modulation, the Additional Multiplication Method (AMM) algorithm is then applied to reduce computational complexity during frequency spreading operations by optimizing matrix multiplications and reducing redundant arithmetic operations. The signal is processed by the Joint Optimization Scheme (JOS) algorithm for PAPR reduction. The system then calculates the PAPR value. If the PAPR is above the defined threshold, the optimization process continues otherwise the optimized signal proceeds to the next stage. Once the transmitter processing is completed, the signal passes through the channel model. First, channel fading is applied using the 207-TU multipath model to simulate realistic propagation conditions. Additive White Gaussian Noise (AWGN) is then added to represent thermal noise effects at different SNR levels.

At the receiver, the Equalization and Cascaded LMS-RLS (ECLS) algorithm is applied to mitigate channel distortion and inter-symbol interference (ISI). The hybrid equalizer combines the stability of LMS with the fast convergence of RLS to achieve improved adaptation performance. A Decision Feedback Equalizer (DFE) further enhances signal recovery by canceling post-cursor ISI using previously detected symbols. The equalized signal is then passed to the OQAM demodulator, where the offset components are recombined to reconstruct complex QAM symbols. These symbols are decoded by the STBC decoder to recover the transmitted data from multiple antennas. Finally, the Bit Error Rate (BER) is calculated by comparing the transmitted

and received bits. If the BER evaluation for the current SNR iteration is complete, the data is stored otherwise the simulation continues for the next SNR value. The process repeats until all SNR levels are evaluated and the final performance results are recorded.

3.6 Additional Multiplication Method at the Transmitter

For this part, an AMM based FBMC OQAM transmitter is proposed to reduce computational complexity. Instead of using the conventional FBMC implementation, the proposed method employs a frequency spreading approach to perform the FBMC filtering operation in the frequency domain. This reduces the overall processing burden while maintaining the fundamental characteristics of the FBMC waveform. In order to evaluate the efficiency of the proposed method, two complementary measures are adopted. First, the computational complexity is assessed using MATLAB execution time (time lapse), where the processing time required to generate the FBMC signal is recorded under identical simulation conditions. This provides a practical indication of the reduction in computational effort.

Second, the arithmetic complexity is reduced by modifying the complex multiplication process [169]. The proposed formulation replaces the conventional implementation requiring four real multiplications and two real additions with a reduced form that uses only three real multiplications and three real additions. Since real multiplications are more computationally demanding than additions, this approach further lowers the overall complexity. By combining the AMM-based frequency spreading with reduced-complexity arithmetic operations, the proposed method achieves improved implementation efficiency without altering the fundamental FBMC OQAM signal structure.

3.6.1 Block Diagram of AMM

Figure 3.6 below shows block diagram of MIMO FS-FBMC with proposed AMM method at the transmitter part.

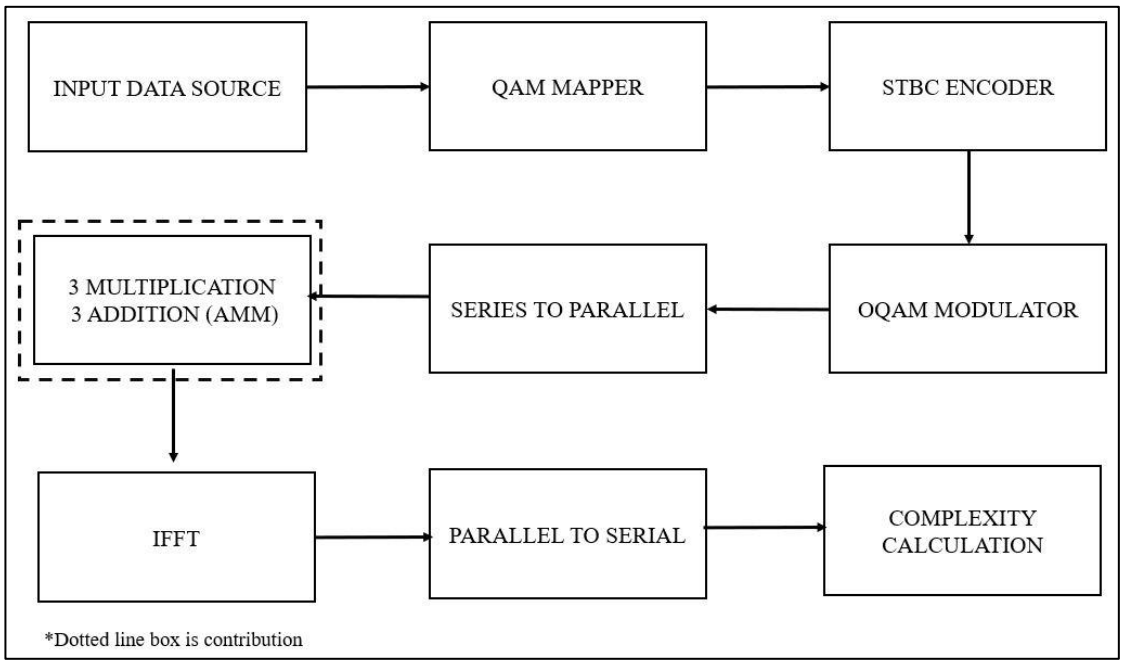

Figure 3.6 Complexity Reduction Techniques Using AMM

The transmitter operation begins with the input data source, where a binary bit stream is generated to represent the information symbols. These bits are grouped according to the selected modulation order M=16, where every four bits form one complex QAM symbol. The grouped bits are then mapped into complex constellation points using the QAM mapper, where each bit group is converted according to the predefined QAM constellation.

The generated QAM symbols are subsequently passed to the STBC encoder configured for a 4×4 MIMO system. The STBC encoder distributes the input symbols across four transmit antennas and multiple time slots based on the orthogonal space-time block coding structure. This process introduces spatial diversity and enhances transmission robustness against fading without increasing the system bandwidth.

Following STBC encoding, the signal undergoes OQAM modulation. In this stage, the real and imaginary components of the complex symbols are separated and staggered by half a symbol duration to maintain real-domain orthogonality which is required for FBMC-based transmission without a cyclic prefix. The resulting OQAM symbols are then converted from serial to parallel format allowing each subcarrier to be processed independently in the frequency domain.

The parallel symbols are next processed using the 3 Multiplication 3 Addition (3M3A) algorithm, also referred to as the Additional Multiplication Method (AMM). This stage optimizes complex multiplication operations required during frequency-domain processing. Instead of performing conventional complex multiplication that requires four real multiplications and two additions, the 3M3A structure reduces the operation to three real multiplications and three additions by algebraic restructuring. Since real multipliers dominate hardware complexity and power consumption, this optimization significantly lowers the computational burden especially in a 2048 subcarrier and 4 transmit antenna configuration where large numbers of complex multiplications are required.

After complexity reduction processing, an Inverse Fast Fourier Transform (IFFT) is applied to convert the frequency-domain subcarrier symbols into the time-domain multicarrier waveform. The IFFT combines all subcarriers to form the composite transmitted signal for each antenna. The resulting time-domain samples are then converted from parallel to serial format and preparing the signal for transmission. Finally, computational complexity is evaluated using MATLAB clock coding. Command ‘tic’ was placed on the start of related coding line then ‘toc’ was written towards the end of the code line. The output which is time lapse will appear in the MATLAB command window. This complexity analysis quantifies the reduction in arithmetic operations achieved by the proposed AMM method.

3.6.2 Simulation Flowchart of AMM

Figure 3.7 shows simulation flowchart for transmitter part of MIMO FS-FBMC with proposed AMM method to reduce complexity.

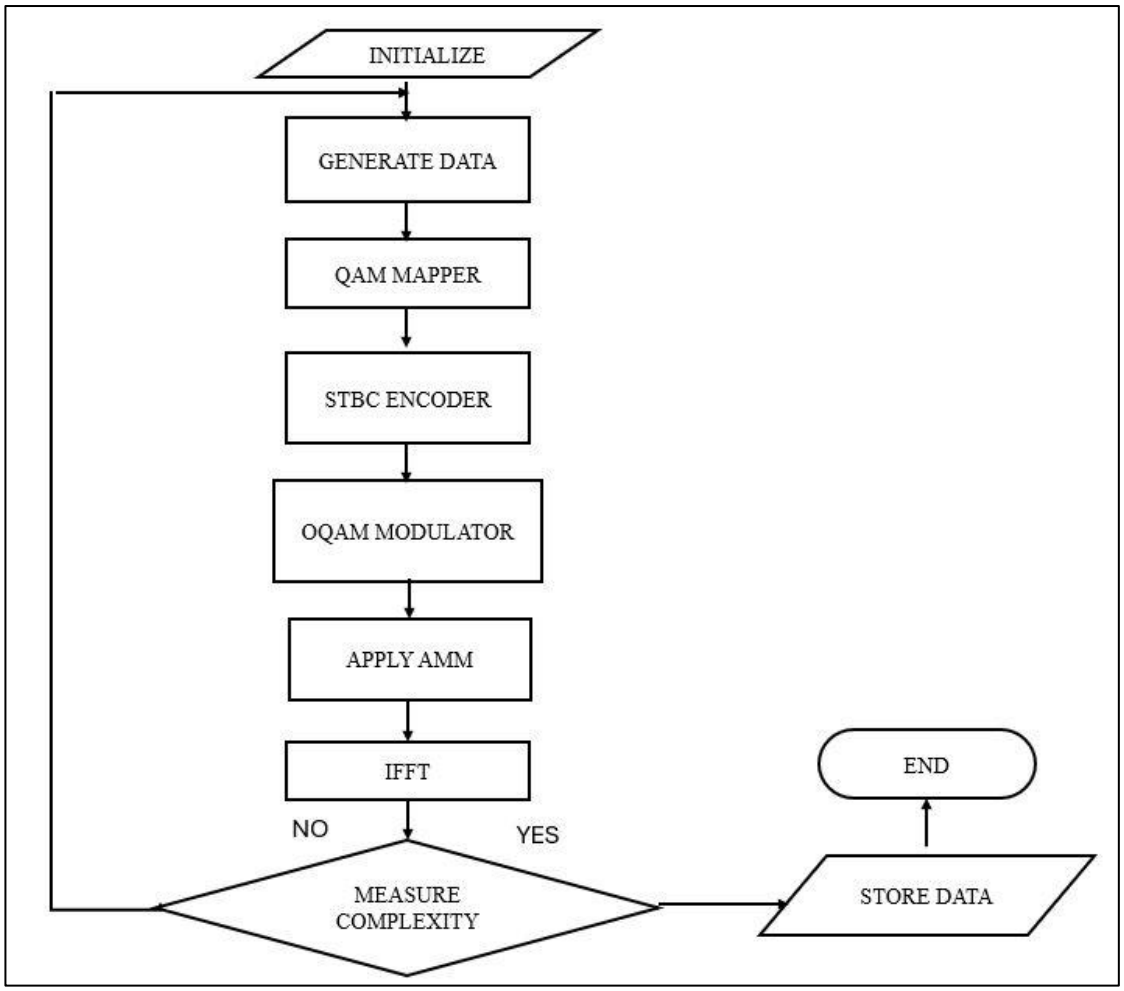

Figure 3.7 Simulation Flowchart of AMM For Complexity Reduction

The proposed transmitter is developed based on a MIMO FS-FBMC architecture, where random binary data is first generated and grouped according to the selected modulation order before being mapped into complex QAM symbols. The mapped symbols are encoded using Space-Time Block Coding (STBC) which distributes the data across multiple transmit antennas and time slots to exploit spatial diversity. The encoded symbols then undergo Offset-QAM (OQAM) modulation where real and imaginary components are staggered in time to preserve real-domain orthogonality, a fundamental requirement in FBMC systems. After OQAM modulation, the symbols are processed using frequency spreading, where each symbol is distributed across adjacent subcarriers according to the prototype filter design.

Since frequency spreading introduces a large number of complex multiplications especially in a MIMO configuration, AMM with 3 multiplication and 3 addition is applied to reduce arithmetic complexity by lowering the number of real multiplications required for each complex operation. This optimization directly targets the most computationally intensive stage of the FS-FBMC transmitter. The processed frequency-domain signals are then converted into time-domain waveforms using the IFFT for each transmit antenna. In order to evaluate the computational efficiency of the proposed design, MATLAB's tic and toc functions are used to measure the total transmitter execution time from STBC encoding to IFFT output.

The process begins with binary sequence generated and grouped into $log_2\ (M)$ bits and form integer symbols a[k]. Then the symbols mapped into complex QAM symbols described as below;

$$d[k] = M_{QAM}\ \{a[k]\} \tag{3.2}$$

$$d[k] =\ d_I\ [k] + jd_Q\ [k] \tag{3.3}$$

Where d_I and d_Q are complex QAM modulated consisting of in-phase and quadrature components. d[k] is a complex symbol representing frequency domain subcarrier data.

QAM symbols then encoded using STBC to exploit spatial diversity in the FS-FBMC.

$$X = STBC(d_1,d_2,\ldots..d_K) \tag{3.4}$$

$$x_i[m], i = 1,2, \ldots N_{Tx} \tag{3.5}$$

Where X is STBC encoded matrix distributing symbols across antenna and time slots. x_i is transmitted signal streams after STBC encoding. N_{Tx} is number of transmit antenna in the MIMO system. Unlike OFDM, FS-FBMC uses OQAM to maintain real orthogonality. The complex output symbol is split into real and imaginary components and staggered in time;

$$s_i[n] = \begin{cases} \mathcal{R}\{x_i[m]\}, & n = 2m \\ \Im\{x_i[m]\}, & n = 2m + 1 \end{cases} \tag{3.6}$$

Where s_i is the real valued of OQAM signal and n is time index. Orthogonality can be

ensure by applying phase rotation;

$$a_{i,k}[n] = s_{i,k}[n]e^{j\phi_{k,n}} \tag{3.7}$$

With k as a subcarrier index in multicarrier system and ϕ is a phase rotation factor used in OQAM to maintain real orthogonality between subcarriers.

In FS-FBMC filtering process is performed in frequency domain via spreading using prototype filter coefficients. The frequency spreading for subcarrier k can be written as;

$$F_i\,[k] = \sum_{\ell=-L}^{L} a_{i,k-\ell}[n]\ \cdot g[\ell] \tag{3.8}$$

Where $g[\ell]$ is prototype filter frequency coefficients and L represents frequency spreading half length. Total of 2L+1 frequency components are used to shape each transmitted symbol. Computational complexity increases during this stage because it introduces multiple complex multiplications.

AMM with 3 multiplications and 3 additions is integrated into the system. First, conventional matrix multiplication can be expressed as;

$$x = a + jb \tag{3.9}$$

$$y = c + jd \tag{3.10}$$

$$x\ \cdot y = (a + jb)(c + jd) \tag{3.11}$$

$$(ac + jad + jbc + j^2bd) \tag{3.12}$$

$$ac + j(ad + bc) + (-1bd) \tag{3.13}$$

$$(ac - bd) + j(ad + bc) \tag{3.14}$$

The final output has real part (ac-bd) and imaginary part j(ad+bc). Operation count has 4 multiplications with 2 additions/subtractions. For AMM, each multiplication consists of

$$z = x \cdot y \tag{3.15}$$

Where x and y is based on (3.9) and (3.10).

To reduce complexity, the algorithm will start with (3.11). To group the variable;

$$ac, ad, bc, bd = 4\ multiplication$$

$$For\ T1\ variable\ a; \tag{3.16}$$

$$ac + ad = a(c + d)$$

$$for\ T2\ variable\ d; ad\ already\ in\ T1 \tag{3.17}$$

$$ad + bd = d(a + b)$$

$$For\ T3\ variable\ c; ac\ already\ in\ T1; \tag{3.18}$$

$$bc - ac = c(b - a)$$

$$Real\ T1 - T2; imaginary\ T1 + T3$$

$$T1 = a(c + d) \tag{3.19}$$

$$T2 = d(a + b)$$

$$T3 = c(b - a)$$

Reconstructing the result as ;

$$\mathcal{R}\{z\} = T1 - T2 \tag{3.20}$$
$$\Im\{z\} = T1 + T3$$

After frequency spreading, signal converted back to time domain using IFFT;

$$x_i\,[n] = \frac{1}{N}\sum_{k=0}^{N-1} Z_i\,[k] e^{j2\pi kn/N} \tag{3.21}$$

With N as a number of subcarrier. The IFFT generate transmit signal waveform ready for further processing.

3.7 Joint Optimization System at The Transmitter

Various PAPR reduction techniques have been proposed to minimize PAPR in the multicarrier modulation. Among of them, companding and clipping are widely adopted due to their simplicity and effectiveness [170]. Clipping is a straightforward PAPR reduction technique that limits the signal amplitude to a predefined threshold. Although clipping can effectively suppress signal peaks, it introduces in-band distortion and spectral regrowth, which may degrade system performance if applied excessively. μ-law companding compress large-amplitude components while preserving low-amplitude signal details. Compared to clipping alone, μ-law companding offers improved distortion control but may provide limited PAPR reduction when used independently.

3.7.1 Block Diagram of JOS with AMM

Figure 3.8 below shows block diagram of MIMO FS-FBMC with proposed JOS method at the transmitter part.

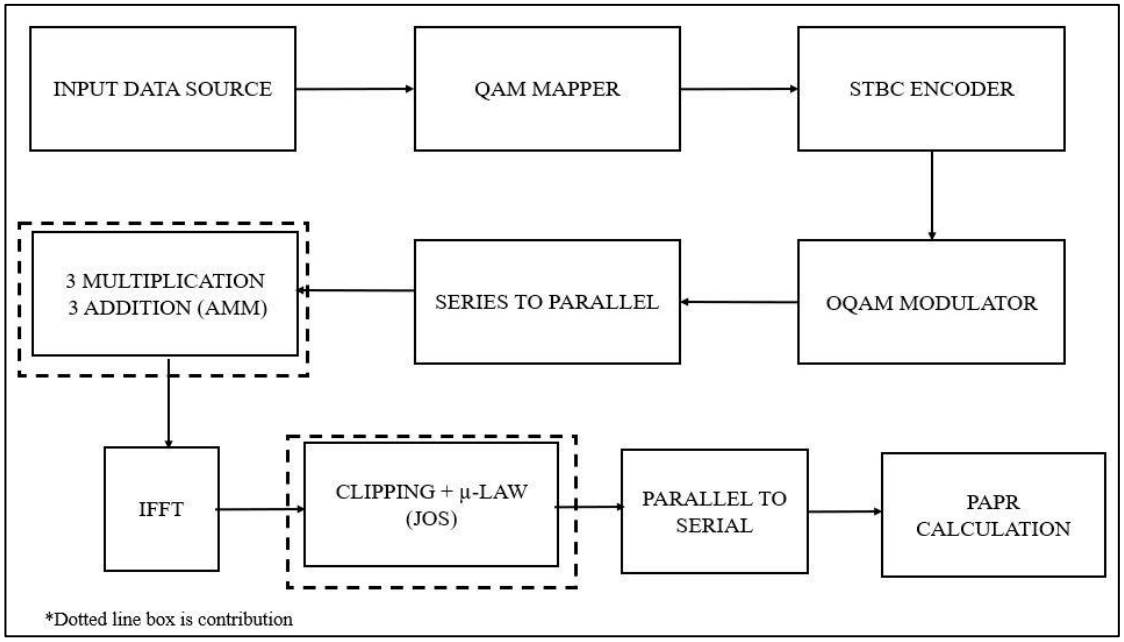

Figure 3.8 Transmitter JOS For PAPR Reduction

This work considers an FBMC OQAM-based transmission system designed to evaluate PAPR reduction using a hybrid companding technique. For PAPR analysis,

only the transmitter section of the system is considered. PAPR is an inherent property of the transmitted time-domain signal and is independent of channel and receiver processing. At the transmitter, the input binary data is first mapped onto a quadrature amplitude modulation (QAM) constellation. Groups of bits are converted into complex symbols according to the selected modulation order. These QAM symbols are then encoded using a space-time (ST) coding scheme to provide transmit diversity across multiple antennas. The encoded symbols are subsequently converted into OQAM symbols by staggering the real and imaginary components in time. The resulting OQAM symbols form the basis of the FBMC waveform.

FBMC modulation is implemented using a frequency spreading approach, which realizes the filtering operation in the frequency domain as an alternative to the conventional polyphase filter bank. AMM with 3 Multiplication and 3 Addition is added to minimize computational complexity. An inverse fast Fourier transform (IFFT) is subsequently applied to generate the time-domain FBMC OQAM signal. Addressing the high PAPR inherent in multicarrier transmission, a hybrid clipping and μ-law companding technique is applied directly to the time-domain signal before transmission. The resulting waveform is then used for PAPR evaluation.

3.7.2 Simulation Flowchart of JOS with AMM

Figure 3.9 shows simulation flowchart for transmitter part of MIMO FS-FBMC with proposed JOS method to reduce PAPR.

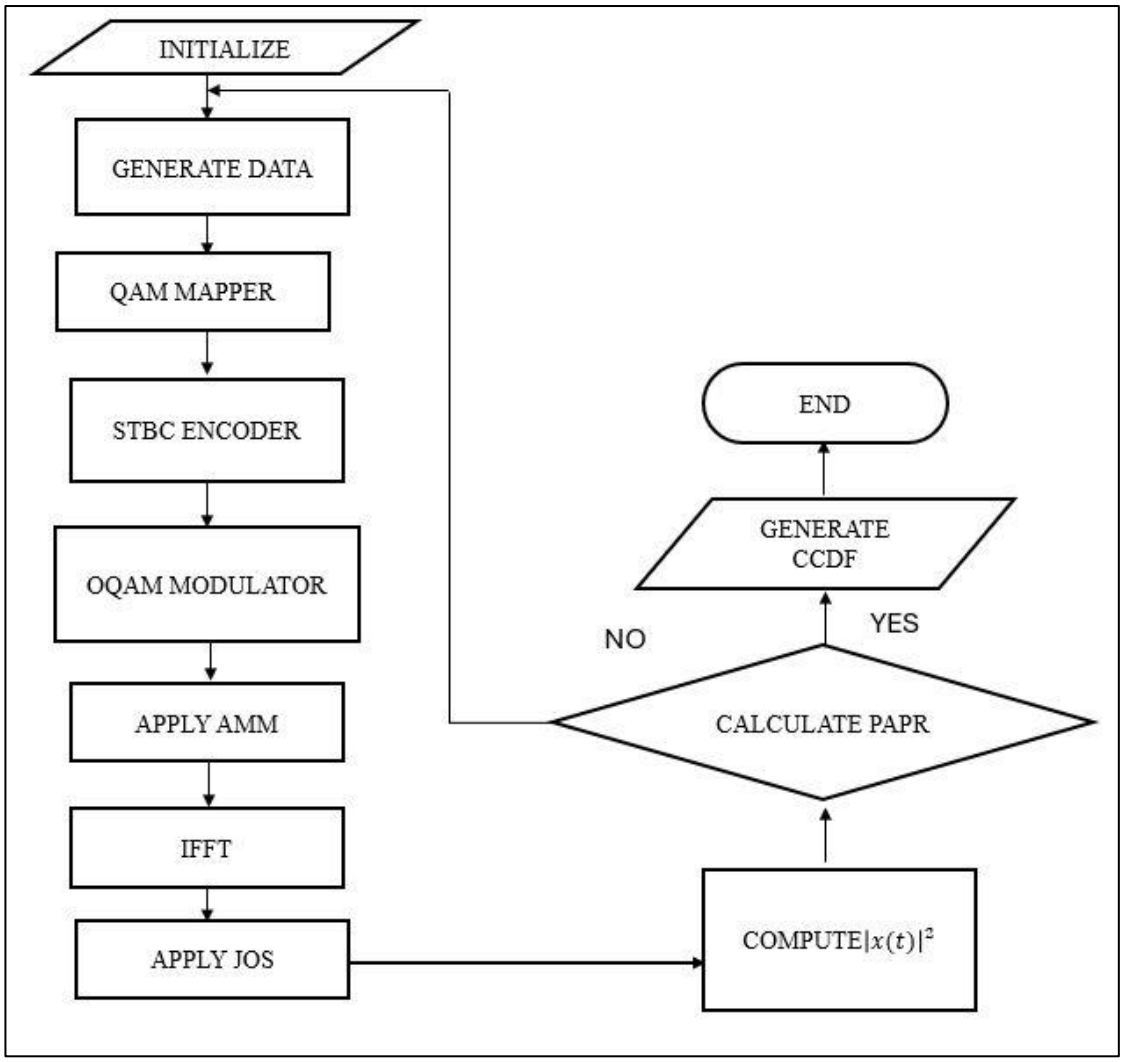

Figure 3.9 Simulation Flowchart Of JOS Method For PAPR Reduction

The simulation procedure begins with the initialization of system parameters, including the number of subcarriers, modulation order, and companding parameters. Random binary data is generated and first mapped onto a QAM constellation. Then, modulated symbols are encoded using a space–time coding scheme to provide transmit diversity. The symbols are then converted into OQAM symbols and processed through FBMC filtering using a frequency spreading implementation. An IFFT is applied to obtain the time-domain FBMC signal, after proposed hybrid clipping and μ-law companding technique is employed to reduce signal peaks. The PAPR is calculated

from the resulting time-domain signal. This process is repeated over multiple frames to obtain reliable statistics, and the complementary cumulative distribution function (CCDF) of PAPR is finally plotted for performance evaluation.

Exploiting the advantages of both methods, a hybrid clipping and μ-law companding approach is proposed in this work. In the proposed scheme, clipping is first used to suppress extreme signal peaks followed by μ-law companding to smoothly compress the remaining signal amplitudes. This combined strategy achieves enhanced PAPR reduction while mitigating the severe distortion associated with conventional clipping. As a result, the hybrid companding technique provides a favorable trade-off between PAPR reduction and signal quality making it suitable for FBMC OQAM systems.

The process started with group of bits according to modulation order. For 16 OQAM;

$$\text{M =16 hence } log_2\,(M) = 4 \tag{3.22}$$

$$\text{Every 4 bits will form one symbol ; } b_k = [b_1, b_2, b_3, b_4] \tag{3.23}$$

The bits then mapped into complex QAM symbols;

$$s(k) = a_k + jb_k \tag{3.24}$$

And can be written as;

$$s_1, s_2, s_3, s_4$$

As the consecutive QAM symbols the main research uses 4x4 antennas.

4Tx STBC codeword is;

$$C = \begin{bmatrix} s_1 & s_2 & s_3 & s_4 \\ -s_2 & s_1 & -s_4 & s_3 \\ -s_3 & s_4 & s_1 & -s_2 \\ -s_4 & -s_3 & s_2 & s_1 \\ s_1^* & s_2^* & s_3^* & s_4^* \\ -s_2^* & s_1^* & -s_4^* & s_3^* \\ -s_3^* & s_4^* & s_1^* & -s_2^* \\ -s_4^* & -s_3^* & s_2^* & s_1^* \end{bmatrix} \tag{3.25}$$

Note that columns represent transmit antennas (q) while rows represent the time slots (t) or FBMC symbol periods. This STBC transmit 4 symbols in 8 time slots instead of using 4 column 4 rows. The transmitted symbol from antenna q at time t is ;

$$x_q\,(t) = C_{t,q} \tag{3.26}$$

Following OQAM modulation, each antenna forms an OQAM symbol by staggering real or imaginary parts.

The expression can be described as;

$$a_q[m,n] = \mathcal{R}\{d_q[m,n]\}\delta_{n\,even} + \mathcal{I}\{d_q[m,n]\}\delta_{n\,odd} \tag{3.27}$$

$d_q[m,n]$ are the complex QAM/STBC symbols integrated to subcarrier m and symbol index n. δ choose even or odd time indices.

Based on system parameter in The simulation parameter shown in Table 3.1 are selected in accordance with the high data rate millimeter-wave framework with necessary adaptation to support FBMC based transmission structure.

Table 3.1, let subcarrier number N = 2048 and K = 4. By using frequency domain prototype filter coefficient, each OQAM symbol can be spread across frequency bins for FS-FBMC system. Hence, antenna q can be described as;

$$X_q\,[k,n] = \sum_{\ell=-L}^{L} F(\ell)a_q[k-\ell,n] \tag{3.28}$$

Where $F(\ell)$ is the frequency domain coefficients of the prototype filter. L is the length of spreading which depends on overlapping factor K.

Insert AMM from (3.2) to (3.28) and expressed the equation as;

$$X_q\,[k,n] = \sum_{\ell=-L}^{L} \mathcal{A}\cdot(F(\ell)a_q[k-\ell,n]) \tag{3.29}$$

To generate time domain transmit waveform, antenna q and symbol time n perform IFFT as;

$$X_q\,[n_0] = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_q\,[k]\, e^{j2\pi k n_0/N}, n_0 = 0, \ldots . N-1 \tag{3.30}$$

Proceed to JOS method, clipping can be expressed as ;

$$X_{c,q}\,[n_0] = \begin{cases} X_q\,[n_0], |x|, & X_q\,[n_0] \le A \\ A\dfrac{X_q\,[n_0]}{\left|X_q\,[n_0]\right|}, & X_q\,[n_0] > A \end{cases} \tag{3.31}$$

Where A is a clipping amplitude threshold and c is the clipped version of $X_q\,[n_0]$. μ-law can mathematically be written as;

$$X_{\mu,q}\,[n_0] = \frac{\ln\left(1 + \mu\dfrac{\left|X_q\,[n_0]\right|}{A}\right)}{\ln(1+\mu)} \cdot \frac{X_q\,[n_0]}{\left|X_q\,[n_0]\right|} \tag{3.32}$$

$X_{\mu,q}\,[n_0]$ is the final signal used for PAPR calculation and transmission. Subscript μ is signal after μ-law companding. μ as a companding factor will controls the strength of compression. Value of this compression parameter is bigger than 1 [171].

To calculate PAPR at the transmitter, the expression is given as ;

$$PAPR_q = \frac{\max\left|X_{\mu,q}\,[n_0]\right|^2}{E\left|X_{\mu,q}\,[n_0]\right|^2} \tag{3.33}$$

$$PAPR_{q,dB} = 10log_{10}\,(PAPR_q) \tag{3.34}$$

$\max\left|X_{\mu,q}\,[n_0]\right|^2$ is a peak signal power with highest signal spike while $E\left|X_{\mu,q}\,[n_0]\right|^2$ represent average signal transmitted power with E acts as an expectation operator. Since the system employs more than one transmit antenna, the overall PAPR can be determined as;

$$PAPR_{MIMO} = \max_{q=1,2,3,4} PAPR_q \tag{3.35}$$

It is possible to evaluate PAPR performance using Complementary Cumulative Distribution Function (CCDF) which can be written as;

$$CCDF = \text{P (PAPR} > PAPR_0) \tag{3.36}$$

With $PAPR_0$ as a given threshold value. In simulation, CCDF can be calculated as ;

$$CCDF(PAPR_0) = \frac{Number\ of\ PAPR\ values\ exceeding\ PAPR_0}{Total\ Number\ of\ transmitted\ symbols} \tag{3.37}$$

From simulation results, a lower CCDF curve indicates better PAPR performance.

3.8 Enhancement Cascaded Least Square at the Receiver

Signal distortion caused by the channel often leads to ISI, which degrades system performance and increases the BER. In order to address this problem, adaptive equalization is commonly used at the receiver to improve signal detection. Among the available adaptive techniques, LMS and RLS algorithms are widely used. The LMS algorithm is simple and computationally efficient but it converges slowly especially in challenging channel conditions. Compares to LMS, the RLS algorithm converges much faster and provides better performance by making use of matrix inversion. However, this comes at the cost of higher computational complexity. In order to balance these trade-offs, this work proposes a hybrid LMS–RLS approach. A training sequence is first employed to guide the RLS algorithm during the initial adaptation stage, allowing it to converge quickly and stabilize the equalizer coefficients. After this stage, the LMS algorithm is used for further adaptation which helps reduce overall complexity while maintaining reliable performance.

3.8.1 Block Diagram of ECLS

Figure 3.10 below shows block diagram of MIMO FS-FBMC with proposed ECLS method at the receiver part.

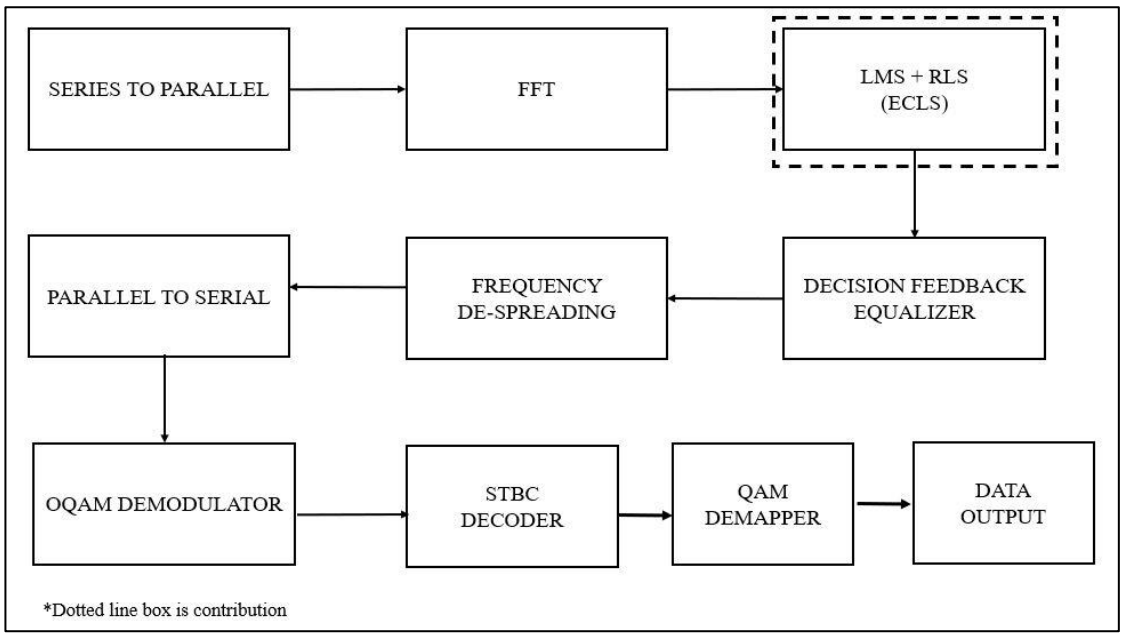

Figure 3.10 ISI Reduction Technique Using ECLS

The receiver block diagram illustrates the stages to reduce ISI in FBMC system. After transmission through the wireless channel, the received FBMC OQAM signal is first converted into the frequency domain using a fast Fourier transform (FFT), enabling subcarrier-wise processing. The FFT output is then go into a cascaded LMS–RLS adaptive equalizer, which compensates for channel distortion and intrinsic interference. In this hybrid approach, the RLS algorithm provides fast initial convergence, while the LMS algorithm ensures low-complexity steady-state tracking.

Following feedforward equalization, a decision device is used to obtain preliminary symbol decisions. These detected symbols are subsequently applied to a decision feedback equalizer (DFE), which utilizes previously detected symbols to cancel residual ISI and intrinsic interference that remains after feedforward equalization. The output of the DFE is then processed by the OQAM demodulator to reconstruct the complex-valued QAM symbols. Finally, QAM demapping is performed to recover the transmitted data bits.

3.8.2 Simulation Flowchart OF ECLS

Figure 3.11 shows simulation flowchart for transmitter part of MIMO FS-FBMC with proposed ECLS method to minimize ISI thus reduce BER.

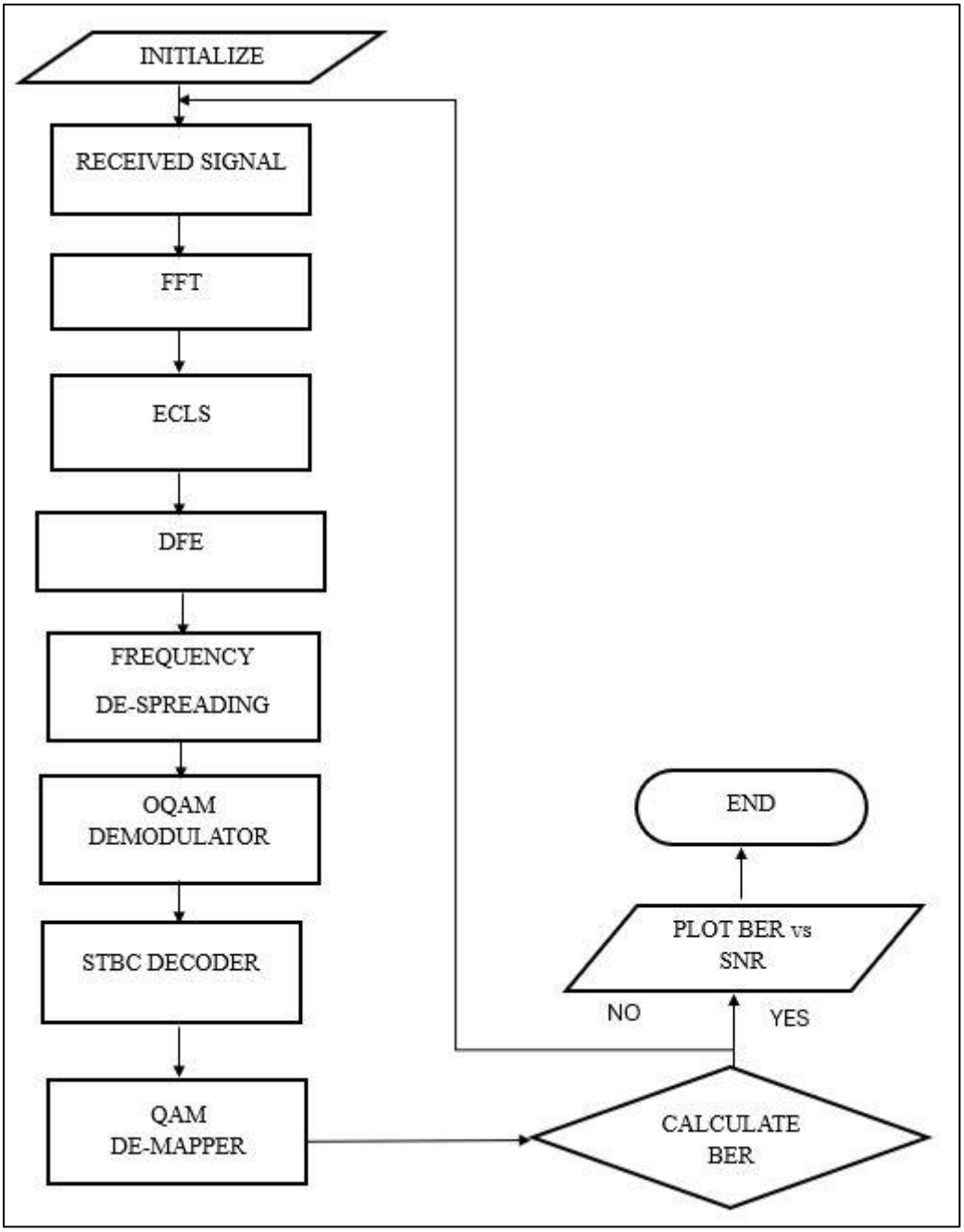

Figure 3.11 Simulation Flowchart of ECLS For ISI Reduction

At the receiver, the process begins with the time-domain signal received from the MIMO channel, which contains the combined contributions from all transmit antennas along with multipath fading and additive gaussian white noise. The signal is

first transformed into the frequency domain using the FFT to enable subcarrier-wise processing suitable for FS-FBMC systems. An ECLS stage is then applied to shorten the effective channel response thus reducing the impact of long multipath components. Instead of allowing the DFE to handle a long channel with many interfering components, ECLS process the received signal to ensure the dominant channel is concentrated within a smaller effective time window. By reducing the effective channel length, the subsequent DFE operates on a simpler channel model and require fewer feedback taps to achieve more stable convergence. After that, DFE mitigates residual ISI by using both feedforward filtering and previously detected decisions. Once equalization is completed, frequency de-spreading is performed to reverse the transmitter's spreading operation. The reason is to reconstruct the original OQAM symbols by recombining subcarrier components.

Next, the OQAM demodulator reverses the staggered real imaginary structure introduced at the transmitter and reconstructs the complex valued symbols. These reconstructed symbols are then passed to the STBC decoder which exploits spatial diversity. This process will combine signals across multiple antennas and time slots according to the space–time coding structure to improve reliability under fading conditions. The decoded symbols are subsequently processed by the QAM demapper to estimate the transmitted bits based on the nearest constellation decision. Finally, the recovered bit sequence is compared with the original transmitted bits to compute the Bit Error Rate (BER) which evaluates the overall system performance.

The process started with received signal from channel. In a multipath wireless channel, the transmitted signal does not arrive through a single path. Instead, it reaches the receiver through multiple delayed and attenuated copies.

For each receive antenna r = 1,2, ….N_{Rx} , Note that n is in time domain, k is subcarrier and m is FBMC symbol time. The signal can be expressed as;

$$y_r[n,m] = \sum_{t=1}^{4} (h_{r,t}[n] * x_t[n,m]) + w_r[n,m] \tag{3.38}$$

$$\mathrm{y}[n,m] = \mathrm{H}[n] * \mathrm{x}[n,m] + \mathrm{w}[n,m] \tag{3.39}$$

Where $y_r[n,m]$ is received signal at Rx antenna, $h_{r,t}[n]$ is multipath channel response, $x_t[n,m]$ transmitted signal that include AMM with JOS and $w_r[n,m]$ is white noise.

Note that (3.39) is in vector form. Next process showing FFT change time domain to frequency domain and the received antennas can be expressed as;

$$Y_r[k,m] = \mathrm{FFT}\{y_r[n,m]\} \tag{3.40}$$

Simplified FFT above can be written as;

$$Y_r(k,m) = \sum_{n=0}^{N-1} y_r\,(n,m)\, e^{-j\frac{2\pi}{N}kn}, k = 0,1,\dots,N-1 \tag{3.41}$$

Stack all receive antennas and MIMO frequency domain model can be written as;

$$\mathrm{Y}(k,m) = \mathrm{H}(k)\mathrm{X}(k,m) + \mathrm{W}(k,m) \tag{3.42}$$

To help reduce ISI, ECLS is employed at this stage. The final ECLS per subcarrier will be expressed like below;

$$\hat{\mathrm{x}}_{\mathrm{ECLS}}(k,m) = \mathrm{G}^{H}(k,m)\,\mathrm{Y}(k,m) \tag{3.43}$$

During this time ECLS will performs as linear equalizer. Note that $\hat{x}$ is equalized and estimated signal. $\mathrm{G}(k,m)$ is the adaptive equalizer and will act as a total ECLS weights. For ECLS output, first the system need to compute the error signal $\mathrm{e}(k,m)$. The equation can be written as;

$$\mathrm{e}(k,m) = \mathrm{d}(k,m) - \hat{\mathrm{x}}_{\mathrm{ECLS}}(k,m) = \mathrm{d}(k,m) - \mathrm{G}^{H}(k,m)\mathrm{Y}(k,m) \tag{3.44}$$

With $\mathrm{d}(k,m)$ as the desired training symbol vector. Although LMS algorithm is simple but it has slow convergence. Training rate is used to update the LMS algorithm and can be expressed as;

$$\mathrm{G}_{\mathrm{LMS}}(k,m+1) = \mathrm{G}(k,m) + \mu\,\mathrm{Y}(k,m)\,\mathrm{e}^{H}(k,m) \tag{3.45}$$

Where μ here is LMS step size applied during symbol training. Value of μ is 0.001

[127][172].

As for RLS, this algorithm has good track of convergence though suffering from complexity. Inverse matrix method is employed to RLS to overcome this problem. It can be defined as;

$$\mathrm{P}(k,m) = \mathrm{R}^{-1}(k,m) \tag{3.46}$$

With gain vector;

$$\mathrm{K}(k,m) = \frac{\mathrm{P}(k,m-1)\mathrm{Y}(k,m)}{\lambda + \mathrm{Y}^{H}(k,m)\mathrm{P}(k,m-1)\mathrm{Y}(k,m)} \tag{3.47}$$

Where λ is a forgetting factor. The value of λ use for this system is 0.995 and it must be between $0 < \lambda < 1$ for non stationary environment [173][174].

Updating matrix inversion form;

$$\mathrm{P}(k,m) = \frac{1}{\lambda}[\mathrm{P}(k,m-1) - \mathrm{K}(k,m)\mathrm{Y}^{H}(k,m)\mathrm{P}(k,m-1)] \tag{3.48}$$

With upadated weights ;

$$\mathrm{G}_{\mathrm{RLS}}(k,m) = \mathrm{G}(k,m-1) + \mathrm{K}(k,m)\, \mathrm{e}^{H}(k,m) \tag{3.49}$$

Putting together updated weight RLS with LMS;

$$\mathrm{G}(k,m) = \alpha\, \mathrm{G}_{\mathrm{RLS}}(k,m) + (1-\alpha)\, \mathrm{G}_{\mathrm{LMS}}(k,m) \qquad 0 \le \alpha \le 1 \tag{3.50}$$

Where α is the weighting factor for LMS-RLS combination in ECLS. Then the ECLS output that goes to DFE is proved to be same like in (3.43).

DFE has feedforward $\mathrm{F_f}$ (k) and feedback filter $\mathrm{F_b}$ (k). The input for DFE is $\hat{\mathrm{x}}_{\mathrm{ECLS}}(k,m)$.

The $\mathrm{F_f}$(k) output can be expressed as ;

$$\mathrm{u}(k,m) = {F_f}^{H}(k)\, \hat{\mathrm{x}}_{\mathrm{ECLS}}(k,m) \tag{3.51}$$

The feedback cancellation uses past detected symbols;

$$\hat{\mathrm{x}}_{\mathrm{DFE}}(k,m) = \mathrm{u}(k,m) - \sum_{i=1}^{L_b} F_{b_i}^{H}(k)\,\tilde{\mathrm{x}}(k,m-i) \tag{3.52}$$

Where L_b is feedback length and $\tilde{\mathrm{x}}(k,m-i)$ act as decision to cancel post-cursor ISI effects.

After that DFE will decide the symbol using slicer Q to find nearest QAM/OQAM constellation point. It can be expressed as;

$$\tilde{\mathrm{x}}(k,m) = Q(\hat{\mathrm{x}}_{\mathrm{DFE}}(k,m)) \tag{3.53}$$

Reconstruct back complex symbols by separating real and imaginary parts;

$$\hat{s}(k,m) = \Re\{\tilde{x}(k,m)\} + j\,\Im\{\tilde{x}(k,m+1)\} \tag{3.54}$$

Where $\hat{s}(k,m)$ is estimated STBC symbol. This group of symbols will decode and normalize to;

$$\hat{\mathrm{s}}(k,m) = \frac{\mathrm{H}^{H}(k)\,\widetilde{\mathrm{X}}(k,m)}{\parallel \mathrm{H}(k) \parallel^2} \tag{3.55}$$

Which $\parallel \mathrm{H}(k) \parallel^2$ as channel power normalization, $\widetilde{\mathrm{X}}(k,m)$ as an equalized received signal after DFE, $\mathrm{H}^{H}(k)$ as conjugate transpose of channel.

$$\parallel \mathrm{H}(k) \parallel^2 = \sum_{r=1}^{N_R}\sum_{t=1}^{N_T}\left|h_{r,t}(k)\right|^2 \tag{3.56}$$

3.9 Summary

The methodology outlines the design of the hybrid clipping and μ-law to reduce PAPR, the mathematical structure of the proposed complex multiplication, equalization and adaptive algorithms used to mitigate distortion and improve convergence. This includes the derivation and implementation of the proposed hybrid LMS–RLS algorithm, which aims to accelerate convergence and stabilize error minimization compared to conventional methods. The integration of AMM, JOS and ECLS is explained to demonstrate how each method contributes to improved symbol recovery in the presence of MIMO interference. Finally, the performance evaluation metrics BER and PAPR with simulation parameters are defined.

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Introduction

This section presents the simulation results and corresponding discussions for evaluating the performance of the proposed MIMO FS-FBMC system. Key performance metrics such as BER and PAPR are analyzed under various operating conditions. At the transmitter, Additional Multiplication Method (AMM) with 3M3A is assessed in terms of computational complexity reduction and its influence on overall system efficiency. The impact of the Joint Optimization System (JOS) by combining clipping and μ-law companding is examined to evaluate its effectiveness in reducing PAPR while maintaining signal quality. At the receiver, the Enhancement Cascaded Least Squares (ECLS) algorithm which integrates LMS and RLS is evaluated for its capability to mitigate ISI and improve BER performance. Furthermore, the inclusion of STBC through the 4×4 antenna structure is analyzed to determine its contribution and its reliability under fading channel conditions. The results are compared with conventional schemes to analyze performance improvements, complexity trade-offs and robustness gains. Detailed discussions are provided to explain the observed trends based on system design principles and theoretical foundations.

4.2 Performance of JOS to Reduce PAPR

This section focuses on the performance evaluation of the proposed JOS for PAPR reduction in the MIMO FS-FBMC system. Due to the multicarrier structure and overlapping subcarriers in FBMC the transmitted signal typically exhibits high PAPR which reduces power amplifier efficiency and increases nonlinear distortion. The proposed JOS method is introduced at the transmitter to mitigate this limitation by optimizing the time-domain signal characteristics prior to transmission. Comparative evaluations with conventional or basic schemes are also presented to highlight the advantages of the proposed approach.

4.2.1 Comparison of PAPR Reduction Technique

The PAPR performance of the proposed MIMO FS-FBMC system is evaluated under four different configurations. The original signal without any reduction technique, A-law companding, μ-law companding and clipping. The original configuration serves as a baseline to illustrate the high PAPR characteristic of multicarrier FBMC signals. Clipping is a simple and widely used PAPR reduction method that limits the peak amplitude of the time-domain signal to a predefined threshold. Companding techniques such as A-law and μ-law apply nonlinear compression to the signal amplitude before transmission and expand it at the receiver. These methods reduce large peaks while preserving smaller signal components. The comparative analysis among these methods highlights the trade-off between PAPR reduction capability and signal distortion effects in the proposed system.

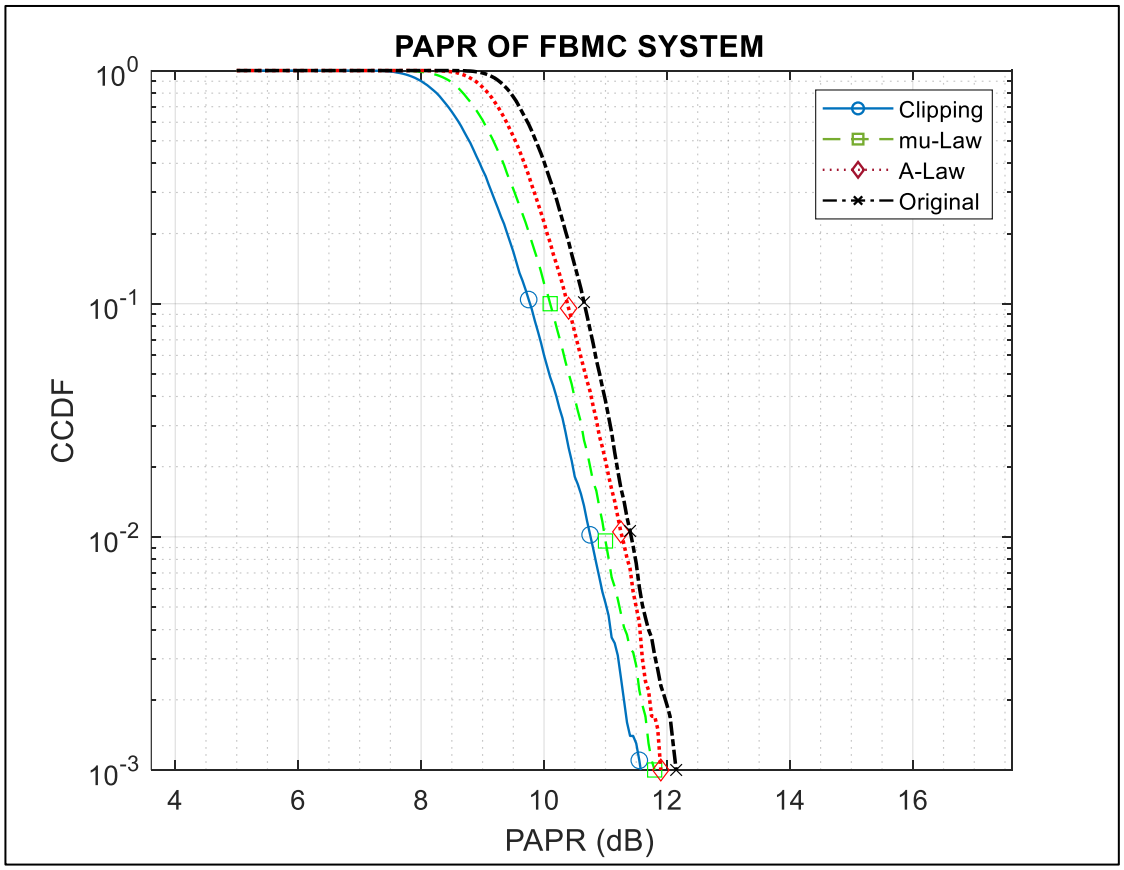

Figure 4.1 Comparison Of PAPR Reduction Technique

Table 4.1
Percentage Improvement PAPR Reduction Technique

CCDF Value (10^{-1})		
	PAPR (dB)	Percentage improvement (%)
Original	10.65	
A-Law	10.40	2.35
μ-Law	10.10	5.16
Clipping	9.75	8.45

Table 4.1 above shows the outcome from PAPR reduction technique in the transmitter. Referring to Figure 4.1 we can notice the gap between original system without reduction method compared to the one with reduction methods. The percentage improvement results show that all three techniques provide noticeable PAPR reduction compared to the original signal. Among them, the A-law based method achieves about 2.35% improvement indicating a moderate reduction in peak power while maintaining signal characteristics. This is because A-law favoring small amplitude signal and utilizes a piecewise characteristic where signals below the 1/A threshold are processed linearly [15]. The μ-law companding technique performs better by offering around 5.16% improvement. This is because μ-law applies stronger logarithmic compression to high-amplitude signal components referring to (3.32). This will effectively suppressing large peaks that commonly occur in multicarrier FS-FBMC signals due to subcarrier superposition. The clipping method shows the highest improvement at approximately 8.45%, demonstrating its strong ability to suppress large peaks because this technique directly limits the signal amplitude to a predefined threshold leading to the most significant peak suppression among the evaluated methods. Overall, these results confirm that although all methods reduce PAPR compared to the original signal, clipping provides the most significant reduction followed by μ-law and then the A-law.

This section presents the results of standalone PAPR reduction methods. The next subsection compares these methods with the hybrid PAPR reduction techniques.

4.2.2 Comparison Method Clipping Filtering (CF) And JOS

This section presents the performance analysis of the proposed Clipping–Filtering (CF) method and the Joint Optimization System (JOS) for PAPR reduction in the MIMO FS-FBMC system. The hybrid clipping filtering approach combines amplitude limitation with spectral filtering to suppress peak regrowth while reducing out-of-band radiation caused by nonlinear distortion. The proposed JOS method enhances peak suppression through an optimized signal processing strategy applied prior to transmission aiming to reduce high-amplitude fluctuations while preserving signal structure and diversity performance. The effectiveness of these advanced techniques is evaluated and compared against the original system and conventional methods to examine improvements in PAPR performance.

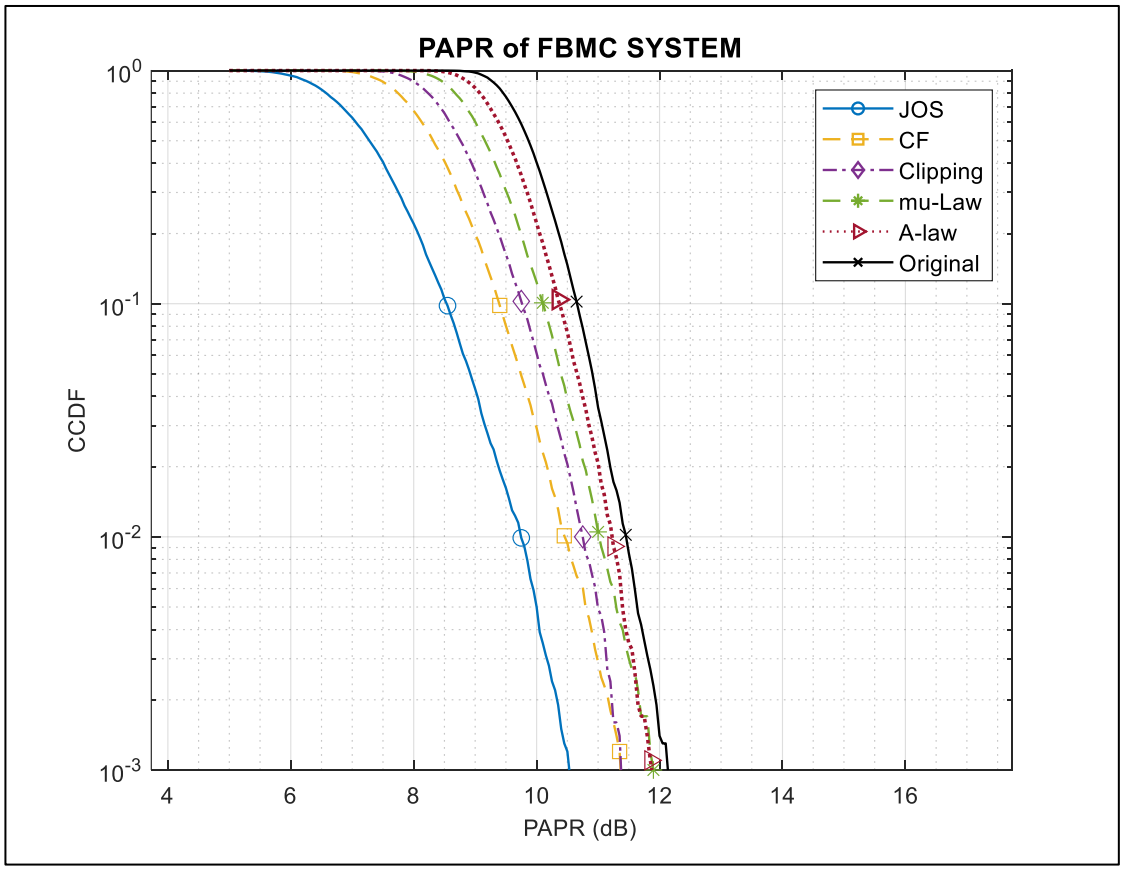

Figure 4.2 Comparison of CF with JOS

Table 4.2
Percentage Improvement Between CF And JOS

CCDF Value (10^{-1})		
	PAPR (dB)	Percentage improvement (%)
Original	10.65	
A-Law	10.40	2.35
μ-Law	10.10	5.16
Clipping	9.75	8.45
CF	9.40	11.74
JOS	8.55	19.72

The simulation results in Figure 4.2 above demonstrate that clipping filtering (CF) method achieves approximately 11.74 % improvement compared to the original system while proposed Joint Optimization System (JOS) provides a more significant improvement of about 19.72%. By referring to value from previous researcher that has more than 10dB when proposed clipping filtering using 2048 subcarrier, JOS proves its efficiency by having only 8.55dB [175]. These outcomes confirm that JOS offers superior peak suppression capability prior to transmission. This technique effectively minimizes large amplitude fluctuations while preserving signal reliability. Conventional basic PAPR reduction techniques such as A-law companding, μ-law companding and clipping were discussed in Section 4.2.1. Filtering was not included in that category because filtering alone does not directly suppress peak amplitudes. It is primarily used to reduce OOB radiation and spectral regrowth caused by nonlinear distortion [175]. Therefore, filtering acts as a complementary enhancement rather than a standalone PAPR reduction technique. In the CF method, clipping will reduce signal peaks by limiting the amplitude while filtering controls spectral distortion resulting in improved PAPR performance compared to clipping alone. Among the evaluated methods, the combination of clipping and μ-law companding provides the most effective basic PAPR reduction performance. Theoretically, this can be explained by amplitude distribution reshaping. In multicarrier FS-FBMC systems, high PAPR originates from the constructive superposition of subcarriers that produce occasional extreme peaks. Clipping enforces a strict amplitude threshold and immediately limiting these peaks [176]. μ-law companding applies logarithmic compression that reduces the dynamic range by compressing higher amplitudes more aggressively than lower ones. Besides that, μ-law reshapes the probability density function of the signal envelope hence reducing the probability of large peaks [177]. This process explains why the

combined clipping and μ-law technique achieves superior PAPR reduction compared to individual basic methods.

After comparing the PAPR reduction methods, the next subsection discusses how different multicarrier modulation schemes affect the PAPR performance

4.2.3 Comparison Of Different Type Of Multicarrier Modulation

This section presents a comparative analysis of the PAPR performance among OFDM, OFDMA and FBMC systems. The objective is to evaluate how different multicarrier structures influence peak power characteristics under similar simulation conditions. By comparing the multicarrier modulation, advantages and limitations of each waveform can be clearly observed. The analysis provides insight into the suitability of each technique for high-efficiency wireless communication systems.

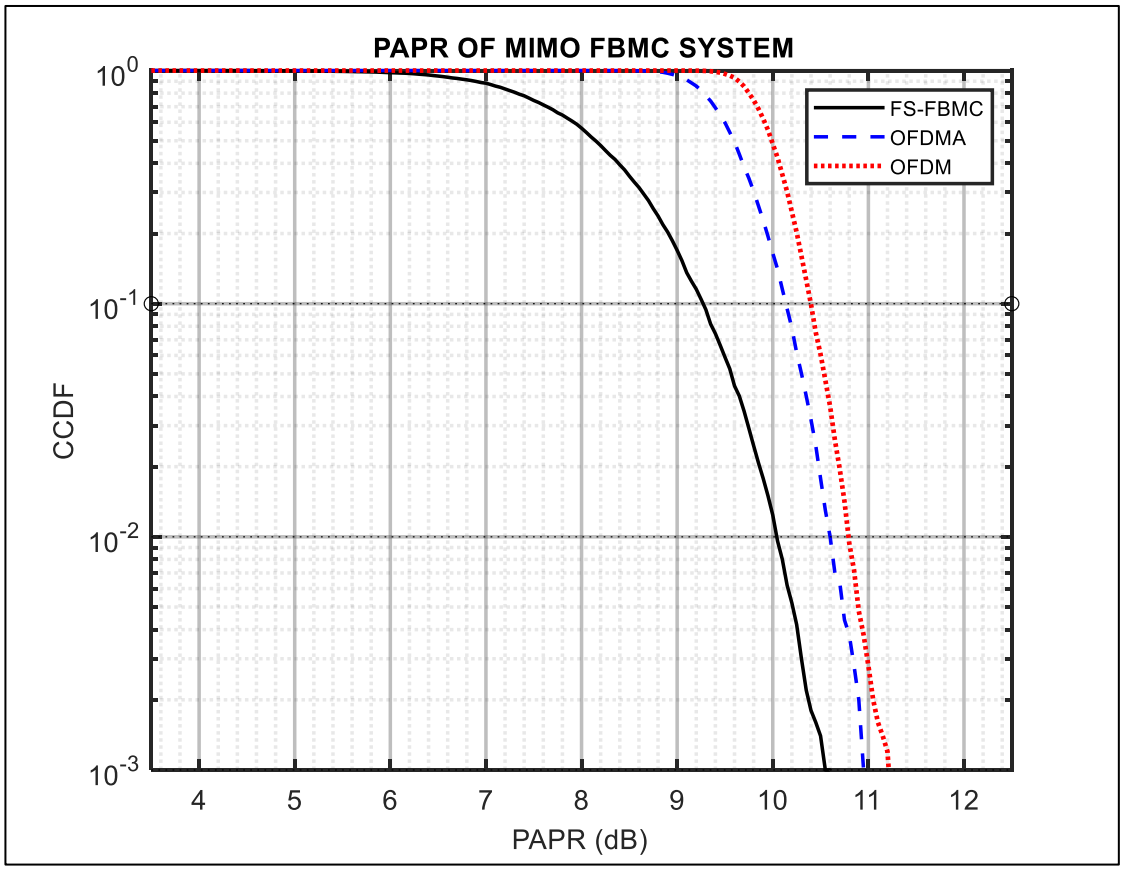

Figure 4.3 Comparison of Multicarrier Modulation

Table 4.3
Percentage Improvement Of Multicarrier Modulation

CCDF Value (10^{-1})		
	PAPR (dB)	Percentage improvement (%)
OFDM	10.42	
OFDMA	10.17	2.40
FBMC	9.27	11.03

Figure 4.3 shows comparison of different type of multicarrier modulation in wireless communication system. Among the three multicarrier schemes, FBMC exhibits the best PAPR performance with 11.03% improvement, followed by OFDMA with 2.40%, while OFDM shows the worst behavior. Value of FBMC with JOS method exhibit 9.27dB compare to the 10dB in the previous research [178]. In OFDM, all subcarriers are transmitted simultaneously with rectangular pulse shaping causing strong constructive superposition of subcarrier peaks. This results in large instantaneous signal amplitudes and high PAPR [179]. OFDMA improves by allocating only a subset of subcarriers to each user which reduces the number of active subcarriers per transmission and lowers the probability of peak alignment [180]. This method leading to a moderate PAPR reduction compared to OFDM. FBMC achieves the lowest PAPR due to its use of well-localized prototype filters and OQAM modulation which can reduce abrupt signal transitions. The OQAM structure transmits real-valued symbols staggered in time hence reducing instantaneous phase alignment among subcarriers. By spreading symbol energy over time, the filtering process minimizes peak occurrences and enhances the smoothness of the signal envelope. Theoretically, the presence of prototype filter referring to (3.8) serves as a pulse-shaping mechanism that can smooths the time-domain waveform and limit sudden transition of amplitude. This process can avoid large constructive peaks. The amplitude distribution of the FBMC signal becomes more controlled compared to OFDM and OFDMA, leading to improved PAPR performance.

FBMC proved it exhibit lower PAPR than the other multicarrier waveforms. The next subsection discusses the different FBMC implementation structures and identifies the most suitable one for the proposed system.

4.2.4 Comparison Type Of FBMC

This section presents a comparative analysis of the PAPR performance between polyphase network (PPN) and Frequency Spreading (FS) systems. The comparison aims to evaluate the impact of different implementation structures on peak power characteristics under identical simulation conditions. By analyzing both methods, the advantages and trade-offs in terms of signal amplitude behavior and power efficiency can be clearly identified. This comparison provides insight into the suitability of each FBMC structure for practical transmission systems.

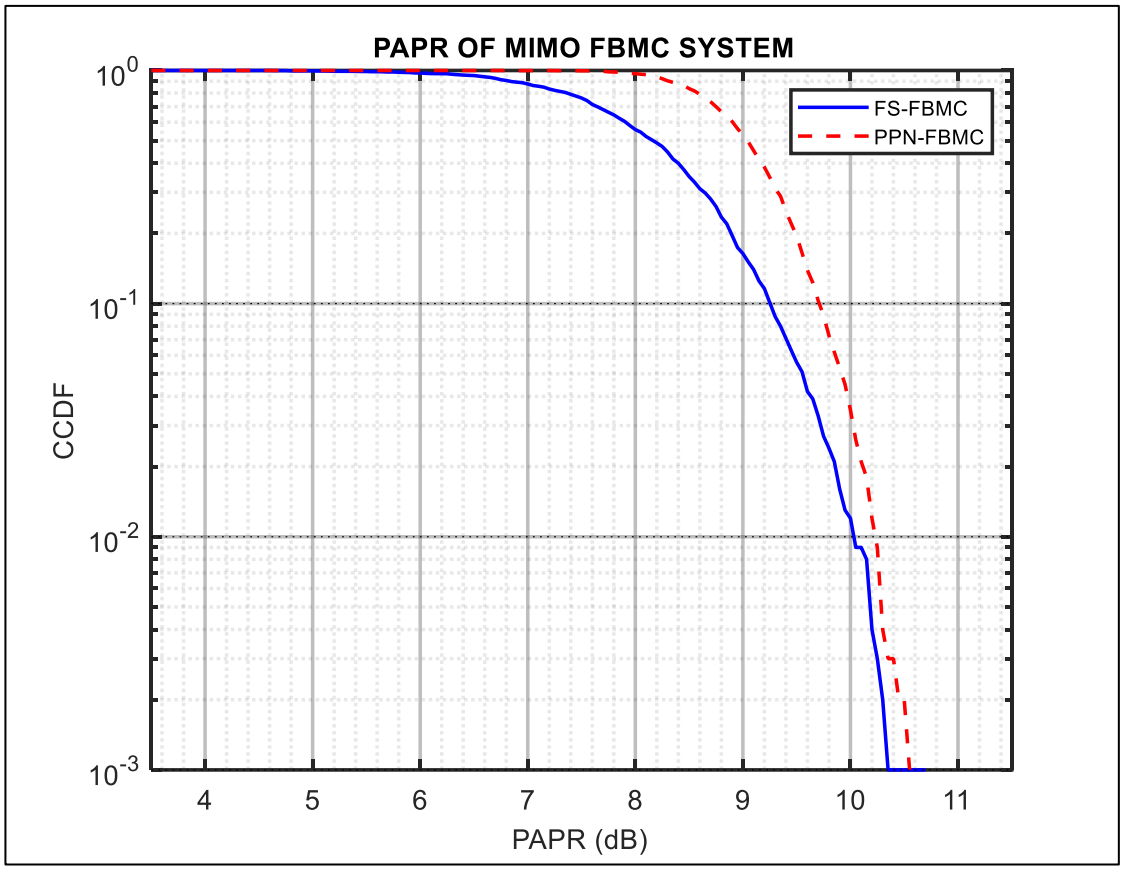

Figure 4.4 Comparison Different Type Of FBMC

Table 4.4
Percentage Improvement between PPN and FS

	CCDF Value (10^{-1})	
	PAPR (dB)	Percentage improvement (%)
PPN FBMC	9.69	
FS-FBMC	9.25	4.54

Figure 4.4 shows the performance of different design FBMC. The comparison between the polyphase network (PPN) implementation and the frequency spreading (FS) approach shows that FS achieves about 4.54% improvement in performance compared to PPN. From a theoretical perspective, this improvement is mainly due to how filtering is handled. In the PPN design, filtering is performed in the time domain using subband filters, which can introduce higher peak variations due to overlapping symbols [96]. PPN is most suitable for a long filter with SISO system. In contrast, the FS method applies filtering in the frequency domain by spreading each data symbol across several subcarriers using well-designed frequency coefficients based on (3.8). This frequency-domain processing provides better control over spectral localization and smoother signal transitions. It can helps reduce abrupt peaks and limits interference. Besides that, filtering process in frequency domain make it easier to combine with MIMO and suitable for higher bandwidth [66]. As a result, FS offers more efficient energy distribution across subcarriers, leading to the observed 4.54% improvement over PPN in FBMC systems.

4.3 Performance of AMM To Reduce Complexity

This section presents the performance evaluation of the proposed Additional Multiplication Method (AMM) based on the 3M3A structure for computational complexity reduction in the FS-FBMC system. The AMM method is introduced at the transmitter to reduce the number of real multiplications required in complex arithmetic operations. This process can enhance processing efficiency without significantly degrading system performance. The effectiveness of the proposed AMM approach is analyzed in terms of BER, computational time (time lapse) and PAPR.

4.3.1 Comparison Of BER Performance

The objective of this analysis is to evaluate the impact of computational complexity reduction techniques on detection reliability and overall system accuracy. Since FS-FBMC involves intensive complex arithmetic operations in filtering and frequency-domain processing, the choice of multiplication method may influence numerical precision and error propagation. Therefore, BER performance is examined to determine whether the proposed AMM technique can maintain signal integrity while

reducing computational complexity. The outcomes will compare its effectiveness against the conventional and Karatsuba implementations.

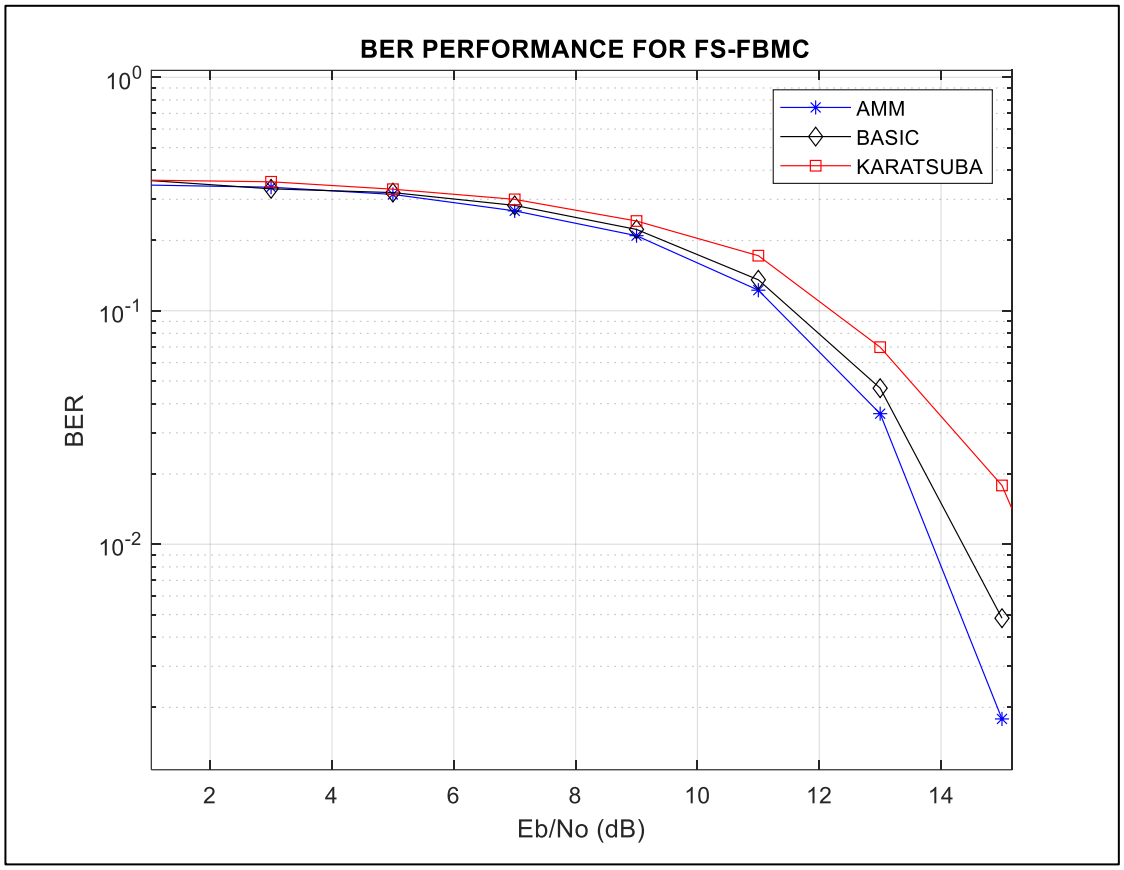

Figure 4.5 Comparison Of Complex Multiplication Method

Table 4.5
Percentage Improvement Complex Multiplication Method

	Eb/No (14dB)	
	BER	Percentage improvement (%)
Basic (4M2A)	0.014	
Karatsuba (3M5A)	0.034	(-)
AMM (3M3A)	0.008	42.85

Table 4.5 stated that Karatsuba method did not have an improvement in BER. Based on Figure 4.5 the BER results show clear performance differences among the 4M2A (basic), 3M3A (AMM), and 3M5A (Karatsuba) complex multiplication schemes. The Karatsuba method exhibits the worst BER performance even though it is designed to reduce computational complexity from $O(n^2)$ to $O(n^{log_2 3})$ [98]. This method increases the number of addition and subtraction operations which leads to higher numerical errors and noise accumulation, especially in finite-precision

implementations [39]. These errors directly degrade detection accuracy resulting in poorer BER performance. Different with Karatsuba, AMM method achieves about 42.85% BER improvement compared to the basic method. This improvement is attributed to its better balance between multiplication reduction and numerical stability by referring to (3.19). While AMM reduces one multiplication, it does not excessively increase the number of additions thus limiting error propagation. As a result, the signal distortion introduced by approximation remains small and lead to improved detection reliability. The basic 4M2A method offers stable performance but with higher computational cost while AMM provides an effective trade-off between complexity and BER performance. Although basic multiplication method is computationally heavier it still maintains full arithmetic precision hence resulting in moderate BER performance. Karatsuba is efficient in reducing multiplications but it is sensitive to noise. This explains why it performs worse than basic and AMM methods in the BER graph.

After comparing the BER performance of the complexity reduction methods, the next subsection evaluates their execution time to determine the improvement in processing efficiency.

4.3.2 Comparison Of Time Lapse

This section presents the computational time analysis of the FS-FBMC system using different multiplication techniques which is proposed AMM (3M3A), the basic conventional method (4M2A) and the Karatsuba algorithm (3M5A). The execution time referred to as time lapse is measured in MATLAB using the tic and toc functions to evaluate the total processing duration of each implementation. By comparing the measured execution times, the effectiveness of the proposed AMM method in improving computational efficiency while maintaining system performance can be clearly demonstrated.

Table 4.6
Comparison Of Complex Multiplication Method

Method	Time	Percentage Improvement (%)
Basic	2.9503 seconds	
Karatsuba	2.7445 seconds	6.98
AMM	2.6409 seconds	10.49

Table 4.6 shows the time required for each method to execute the process. The execution time analysis demonstrates that the basic complex multiplication exhibits the highest computational latency due to its requirement of four real multiplications. By reducing the number of multiplications to three, the Karatsuba method achieves a noticeable reduction in execution time with 6.98% improvement despite an increase in addition operations. The optimized AMM scheme with 10.49% improvement further minimizes computational cost by reducing both multiplication and addition operations resulting in the lowest execution time among the evaluated methods. Importantly, all three schemes exhibit identical BER performance confirming that the proposed complexity reduction does not compromise system reliability.

Following the execution time analysis, the next subsection evaluates the PAPR performance of the complexity reduction methods.

4.3.3 Comparison of PAPR Performance

This section presents the complexity analysis of the FS-FBMC system by evaluating PAPR performance under different multiplication technique which is conventional multiplication method, Karatsuba method and AMM. The objective of this analysis is to investigate how arithmetic complexity reduction techniques influence both computational efficiency and signal peak characteristics. PAPR performance is analyzed to determine whether the proposed AMM technique can reduce processing complexity without degrading peak power characteristics.

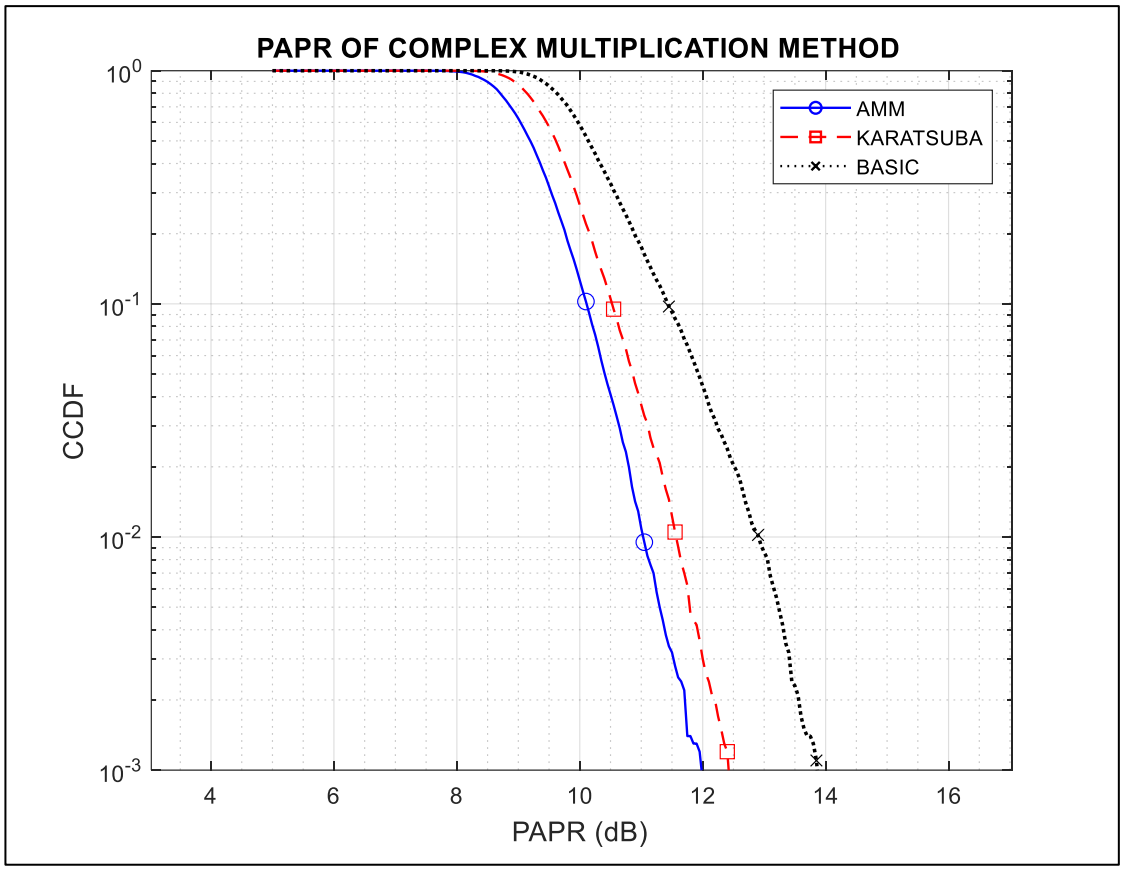

Figure 4.6 Comparison Of PAPR Performance

Table 4.7
Percentage Improvement of Complex Multiplication Method

CCDF Value (10^{-1})		
	PAPR (dB)	Percentage improvement (%)
Basic	11.45	
Karatsuba	10.55	7.86
AMM	10.10	11.79

The PAPR performance of different complex multiplication methods in Figure 4.6 shows a trend that is different from the BER results in Figure 4.5 highlighting that PAPR and BER are influenced by different signal properties. For PAPR, the Karatsuba method performs about 7.86 % better than the basic method, while the AMM method achieves the best performance with around 11.79% improvement over conventional multiplication method. Reducing the number of arithmetic operations particularly multiplication may limit the accumulation of floating-point rounding errors hence improving numerical stability [181].

From a theoretical perspective, PAPR is mainly determined by instantaneous

signal amplitude and peak formation rather than symbol decision accuracy referring to (3.33). The Karatsuba algorithm restructures complex multiplication by combining partial products, which can lead to partial peak smoothing [182]. This explains why Karatsuba shows better PAPR compared to basic method even though it performs poorly in BER. However, the increased number of additions in Karatsuba introduces higher sensitivity to noise and quantization errors which affects BER but does not significantly impact peak amplitudes.

The AMM method, on the other hand, offers a more balanced arithmetic structure. By reducing one multiplication while keeping the number of additions moderate, AMM minimizes excessive peak reinforcement and avoids strong peak regrowth. This leads to a smoother signal envelope resulting in the highest PAPR reduction 11.79% among the methods. Therefore while Karatsuba improves PAPR by 7.86% over basic method, its numerical instability limits BER performance.

4.4 Performance of AMM FS-FBMC to Reduce BER

This section presents the performance evaluation of the proposed Additional Multiplication Method in reducing BER within the FS-FBMC system. The objective is to study the impact of arithmetic complexity reduction on detection reliability under various system configurations. In order to provide a comprehensive analysis, simulations are conducted under different antenna configurations, multicarrier modulation schemes, QAM modulation orders, and FBMC structures particularly focusing on the FS-FBMC implementation. The performance is also examined under different adaptive equalization algorithms and various RLS complexity reduction technique, including variable, inverse, and fixed approaches. By analyzing these parameters collectively, the robustness and effectiveness of the AMM technique in reducing BER across diverse system conditions can be clearly demonstrated.

4.4.1 Different Number of Antennas

This section analyzes the impact of different antenna configurations on the BER performance of the proposed FS-FBMC system. The simulations are conducted using 1×1 (SISO), 2×2 MIMO, and 4×4 MIMO configurations to evaluate the effect of spatial diversity on system reliability.

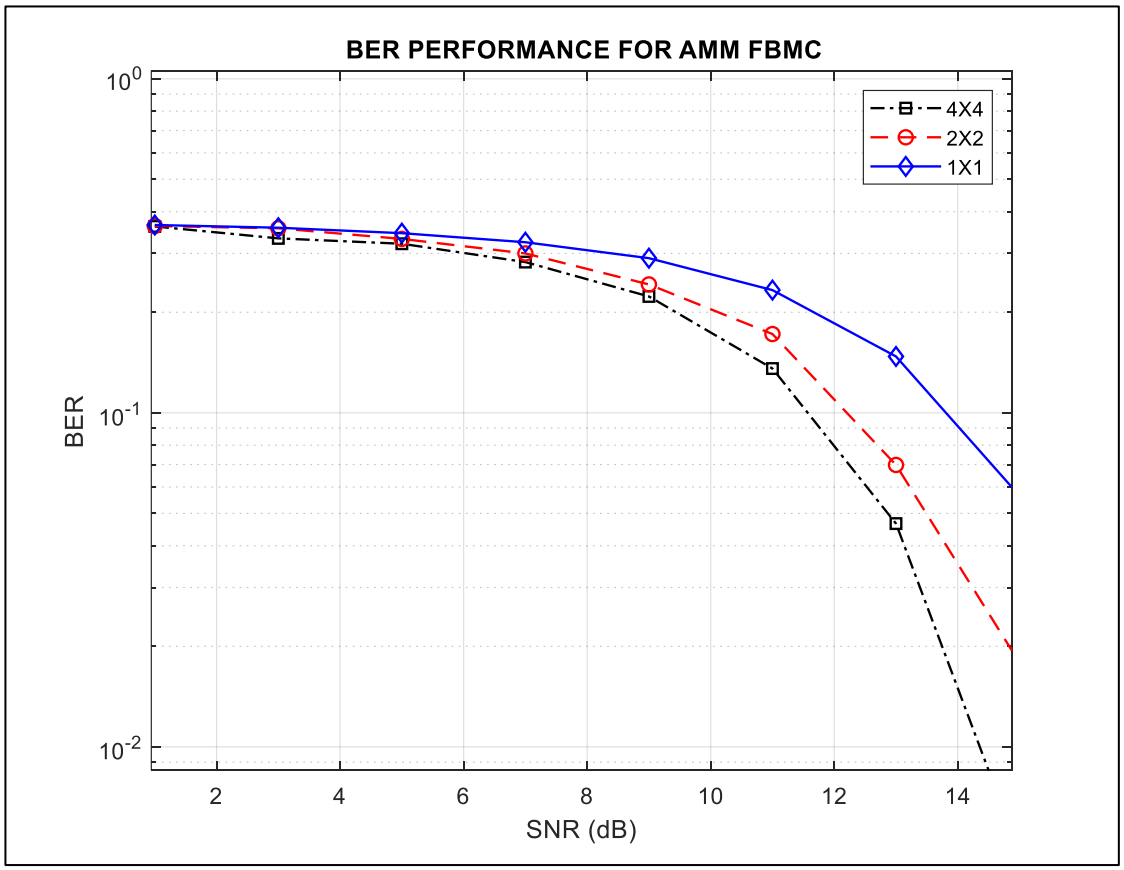

Figure 4.7 Comparison Number Of Antennas For AMM

Table 4.8
Percentage Improvement Number Of Antennas

Eb/No 14 dB		
	BER	Percentage improvement (%)
1X1 (SISO)	0.090	
2X2 (MIMO)	0.036	60
4X4 (MIMO)	0.015	83

Figure 4.7 above compares different number of antennas. 1x1(SISO), 2×2 (MIMO) and 4×4 (MIMO) clearly shows that increasing the number of antennas significantly enhances system performance. As expected, the 4×4 MIMO system

demonstrates the most outstanding performance, achieving approximately 83% improvement over SISO and while 2x2 has 60% improvement compared to SISO. This improvement is strongly supported by MIMO theory [183]. It also prove that better efficiency of AMM FS-FBMC when compare to value from existing literature that has BER value near to 0.01 [161]. Besides that, the system benefits from higher spatial diversity which reduces the probability that all signal paths experience deep fading simultaneously. In a 2×2 MIMO system, diversity already improves reliability compared to SISO by providing multiple independent propagation paths. However, a 4×4 MIMO configuration further increases the diversity order leading to more robust signal detection referring to (3.24). 4x4 antenna means it has 16 maximum diversity which also means the system will has 16 independent signal paths [160]. The receiver can select the best data out of the many choices of signal paths. Diversity gain can be achieved by increasing the number of transmit and receive antennas which improves robustness against fading. 4×4 MIMO proved that it can improve array and beamforming gains which enhance the effective received signal power [184].

After evaluating the effect of the number of antennas on BER performance and proves that 4x4 MIMO antenna has the best outcome, the next subsection compares the BER performance of different multicarrier modulation schemes.

4.4.2 Different Type Of Multicarrier Modulation

This section presents a comparative analysis of the BER performance for different multicarrier modulation schemes OFDM, OFDMA and FBMC. The objective is to evaluate how structural differences in waveform generation and subcarrier processing affect detection reliability. The comparison provides insight into the robustness and suitability of each modulation technique for reliable wireless communication systems.

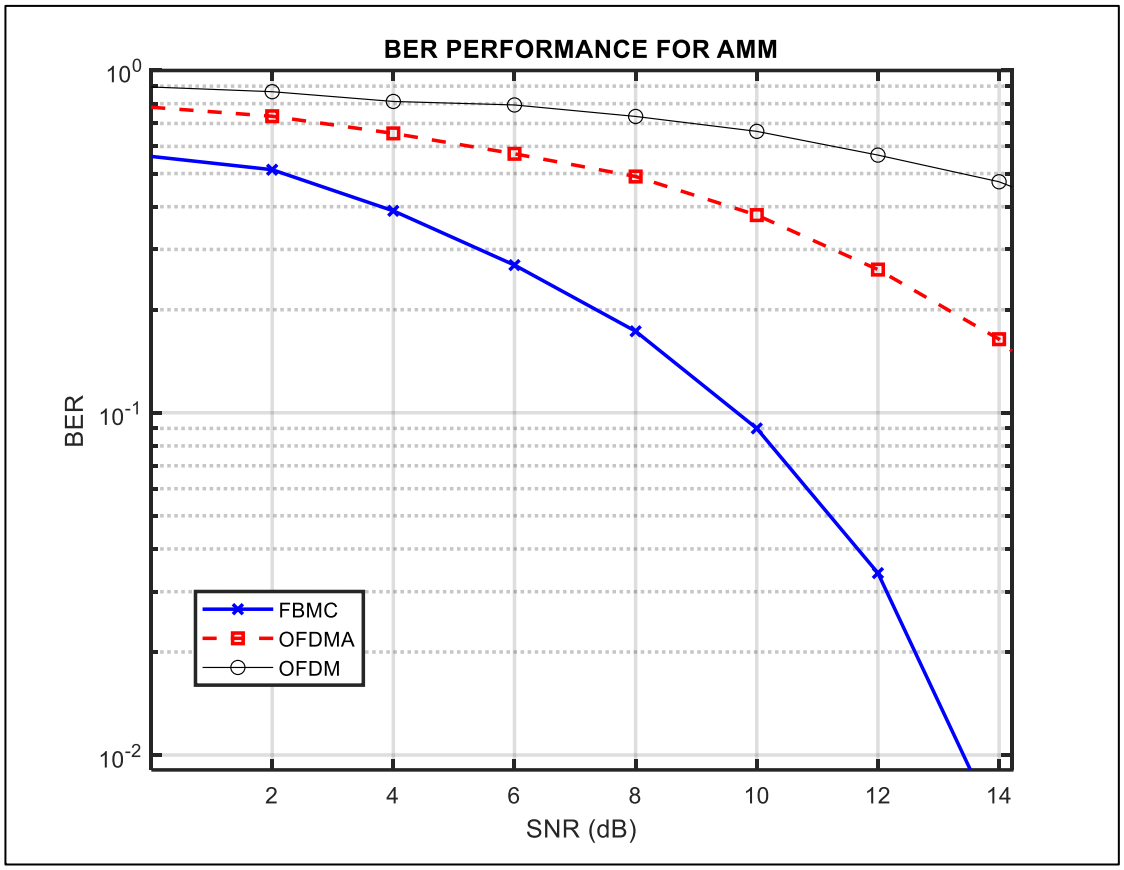

Figure 4.8 Comparison Different Multicarrier Modulation

Table 4.9
Performance Improvement Of Multicarrier Modulation

SNR 14 dB		
	BER	Percentage improvement (%)
OFDM	0.473	
OFDMA	0.164	65.32
FBMC	0.006	98.73

The comparison between OFDM, OFDMA, and FBMC in Figure 4.8 shows that OFDMA achieves about 65.32% improvement, while FBMC provides up to 98.73% improvement over conventional OFDM because OFDM relies on cyclic prefix (CP) compare to FBMC that has prototype filter referring to (3.8). This outcome can be compared with existing research that has SNR up until 6 dB only and shows higher BER compare to the proposed method [79]. In OFDM, all subcarriers are assigned to a single user and a CP is required to mitigate multipath interference. The inclusion of a CP in OFDM introduces overhead that reduces spectral and power efficiency since a portion of the transmitted energy carries redundant information rather than useful data [96]. As a result, more transmit energy is required to achieve the same effectiveness compared to multicarrier schemes without CP such as FBMC. OFDMA on the other hand, divides subcarriers among multiple users thus enabling more efficient resource utilization and improved frequency diversity. By allocating subcarriers based on channel conditions, OFDMA reduces interference and improves robustness which explains the better performance improvement over OFDM. FBMC achieves the highest improvement due to its fundamental design. Unlike OFDM and OFDMA, FBMC does not require a cyclic prefix and instead uses well-designed prototype filters for each subcarrier. This results in excellent spectral localization, lower out-of-band emissions, and reduced inter-carrier interference. Additionally, the use of OQAM allows symbols to overlap in time and frequency without sacrificing orthogonality, leading to higher efficiency and better resilience to channel distortion [66].

After comparing the BER performance of different multicarrier modulation schemes and prove that FBMC has lowest value of BER, the next subsection evaluates the effect of different modulation orders on BER performance.

4.4.3 Different Number Of QAM Modulation

This section presents the BER performance analysis of the proposed system under different QAM modulation orders 16-QAM, 64-QAM, and 128-QAM. The objective is to study how increasing modulation order influences detection reliability and noise sensitivity.

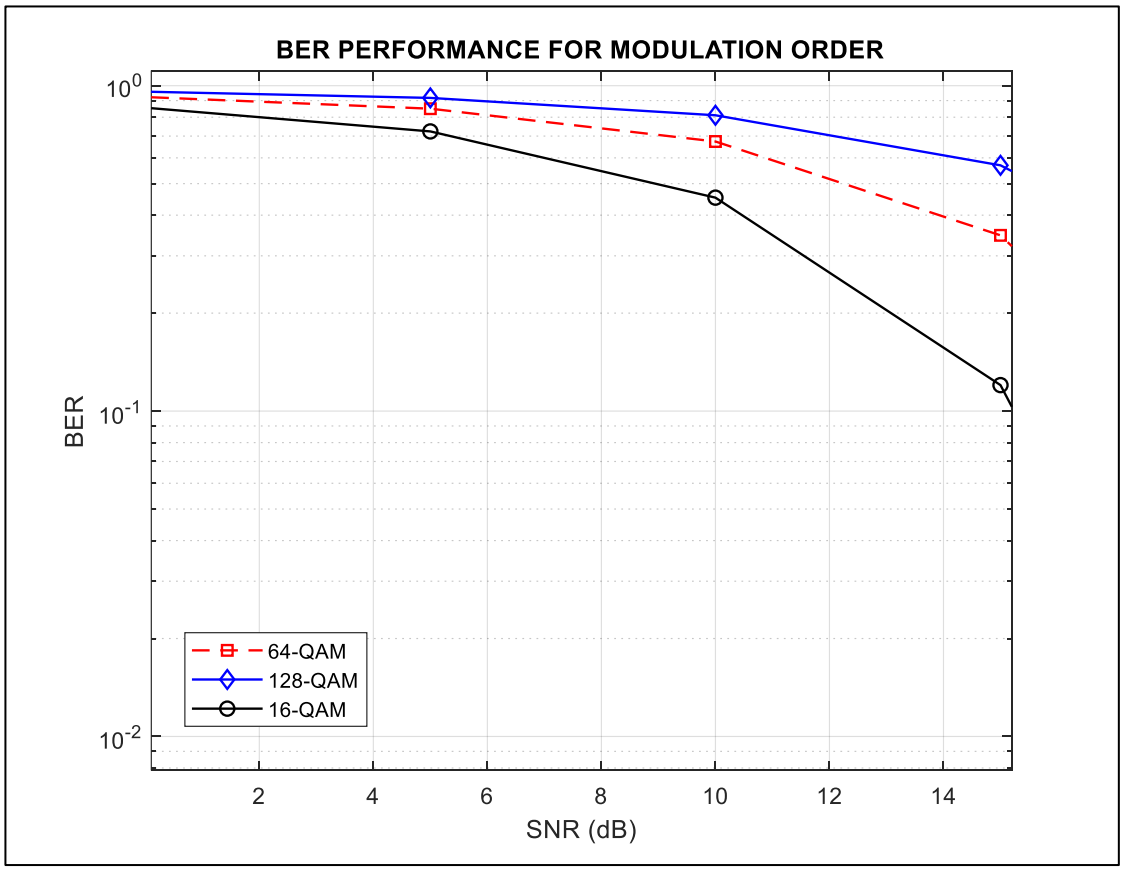

Figure 4.9 Comparison Different Number Of QAM

Table 4.10
Percentage Improvement Of Modulation Order

SNR 14 dB		
	BER	Percentage improvement (%)
128-QAM	0.612	
64-QAM	0.398	34.96
16-QAM	0.157	74.34

Figure 4.9 proves that the BER performance of 16QAM, 64QAM and 128QAM shows a clear dependence on the modulation order. Among the three schemes, 16QAM achieves the lowest BER at the lowest SNR, while 64QAM and 128QAM require

significantly higher SNR values but still exhibit higher BER. This behavior is mainly due to the constellation structure of each modulation scheme referring to (3.22). By referring to outcome in [178], the result shows that value of BER slightly higher than proposed method at 14dB although the BER degrades progressively with number of QAM modulation. Theoretically, in 16QAM, the constellation points are widely spaced, resulting in a large minimum Euclidean distance between symbols [185]. This wide separation makes the system more robust to noise and channel impairments, allowing reliable symbol detection even at low SNR levels [186].

16QAM provides superior BER performance in noisy conditions with 74.34 percent improvement compared to 128QAM. 64QAM and 128QAM employ a larger number of constellation points within the same signal power range. This leads to closely packed symbols and smaller decision regions. Consequently, even small noise or interference can cause symbol misclassification, which increases the BER. Although higher-order QAM schemes operated at higher SNR to support increased data rates however the improvement in SNR is often insufficient to fully compensate for the reduced symbol spacing [187]. Spectral efficiency is improving as the modulation order increases since more bits are transmitter per symbol by referring to (3.23). However, it can cause the system more susceptible to noise and channel impairments because constellation point distance is decreased. Therefore, higher order modulation schemes are already expected to exhibit higher BER under the same SNR conditions.

After evaluating the effect of different modulation orders on BER performance and proves that 16QAM exhibit lowest BER, the next subsection compares the BER performance of the FS and PPN FBMC structures.

4.4.4 Different Type Of FBMC

This section presents the BER performance comparison between two FBMC implementations Frequency-Spreading FBMC (FS-FBMC) and Polyphase Network FBMC (PPN-FBMC). The objective is to evaluate how the different structures influence detection reliability under identical channel and system settings. Although both approaches are based on the same FBMC principle and prototype filtering, FS-FBMC performs filtering in the frequency domain while PPN-FBMC through a time-domain.

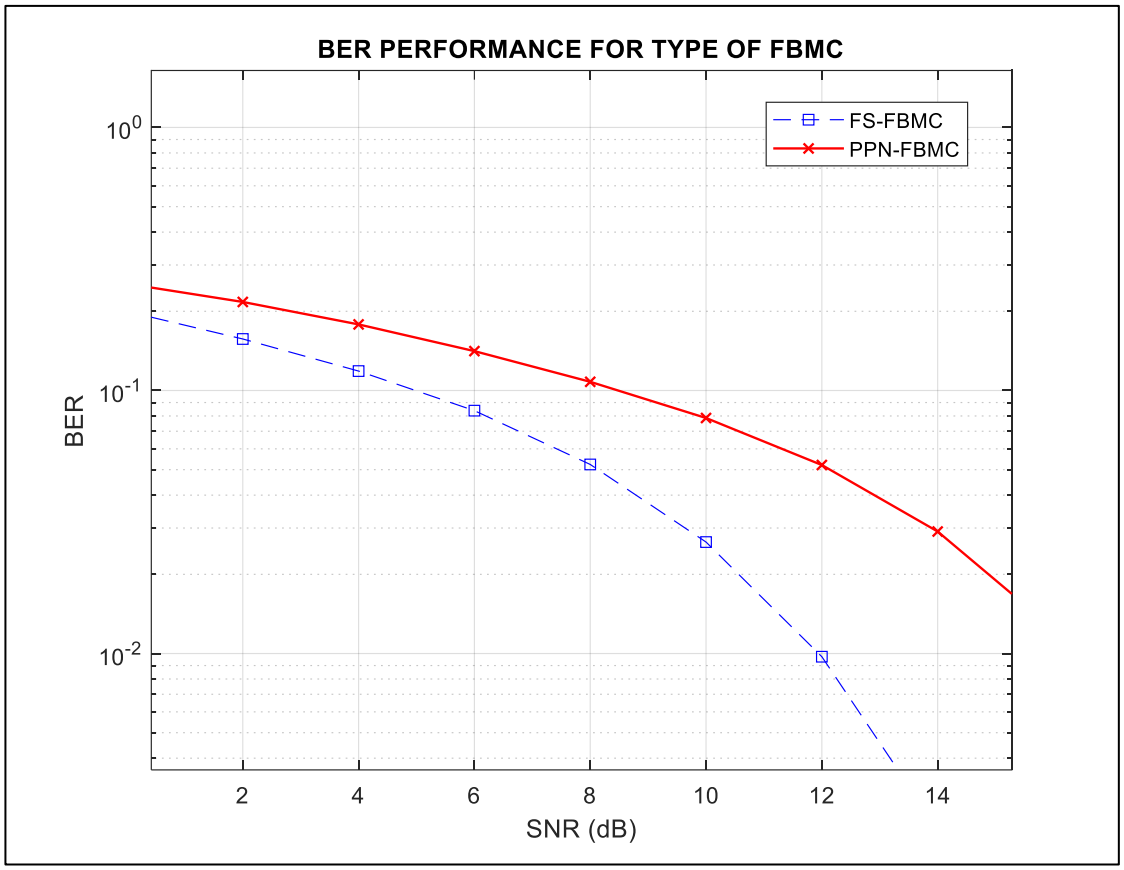

Figure 4.10 Comparison Different Type Of FBMC

Table 4.11
Percentage Improvement Type Of FBMC

	SNR 13 dB	
	BER	Percentage improvement (%)
PPN-FBMC	0.038	
FS-FBMC	0.004	89.47

Figure 4.10 shows a comparison between two different FBMC approaches. The frequency spreading (FS) structure yields approximately 89.47% BER improvement over the polyphase network (PPN) structure due to its superior frequency-domain filtering capability and enhanced interference localization. This improvement is consistent across SNR values and becomes more pronounced in noisy and frequency-selective channel conditions. In order to justify more about the performance of the system, the outcomes can be compared with value from previous research in [57][188]. Although the previous research has smooth beamforming and larger value of SNR, the proposed method outperform both research in terms of BER. FS typically involves fewer rounding operations in its arithmetic chain compared to multiple stages in PPN structure which may reduce rounding error accumulation [26]. As a result, improved numerical stability and more precise equalization collectively contribute to the lower BER observed in the FS-FBMC system. By performing symbol shaping and filtering in the frequency domain, FS effectively mitigates intrinsic ISI and ICI while enabling efficient frequency-domain equalization [188]. For PPN, its structure relies on long time-domain filters, which increase sensitivity to channel dispersion and intrinsic interference [59]. Although mathematically equivalent to FS in ideal conditions, the time-domain filtering process is more sensitive to synchronization errors for example timing offsets and channel distortion. In frequency-selective or MIMO fading channels, ISI and intrinsic interference may not be perfectly compensated especially when equalization is performed per subcarrier without fully accounting for filter memory as we can see from (3.38). This can cause slight constellation distortion leading to higher BER.

After comparing the BER performance of the FS and PPN structures and justify that FS has better outcome in terms of matrix multiplication compare to PPN, the next subsection evaluates the performance of different adaptive algorithms.

4.4.5 Different Type Of Adaptive Algorithm

This section presents the BER performance analysis of the proposed FS-FBMC system using different adaptive equalization algorithms Recursive Least Squares (RLS), Least Mean Squares (LMS) and a configuration without adaptive algorithm. The objective is to evaluate how adaptive filtering techniques influence detection reliability under fading channel conditions. While the system without adaptation serves as a baseline, LMS and RLS algorithms are implemented to mitigate channel distortion and interference through iterative coefficient updates. By comparing these approaches the effectiveness of each adaptive algorithm in improving BER performance behavior can be clearly evaluated.

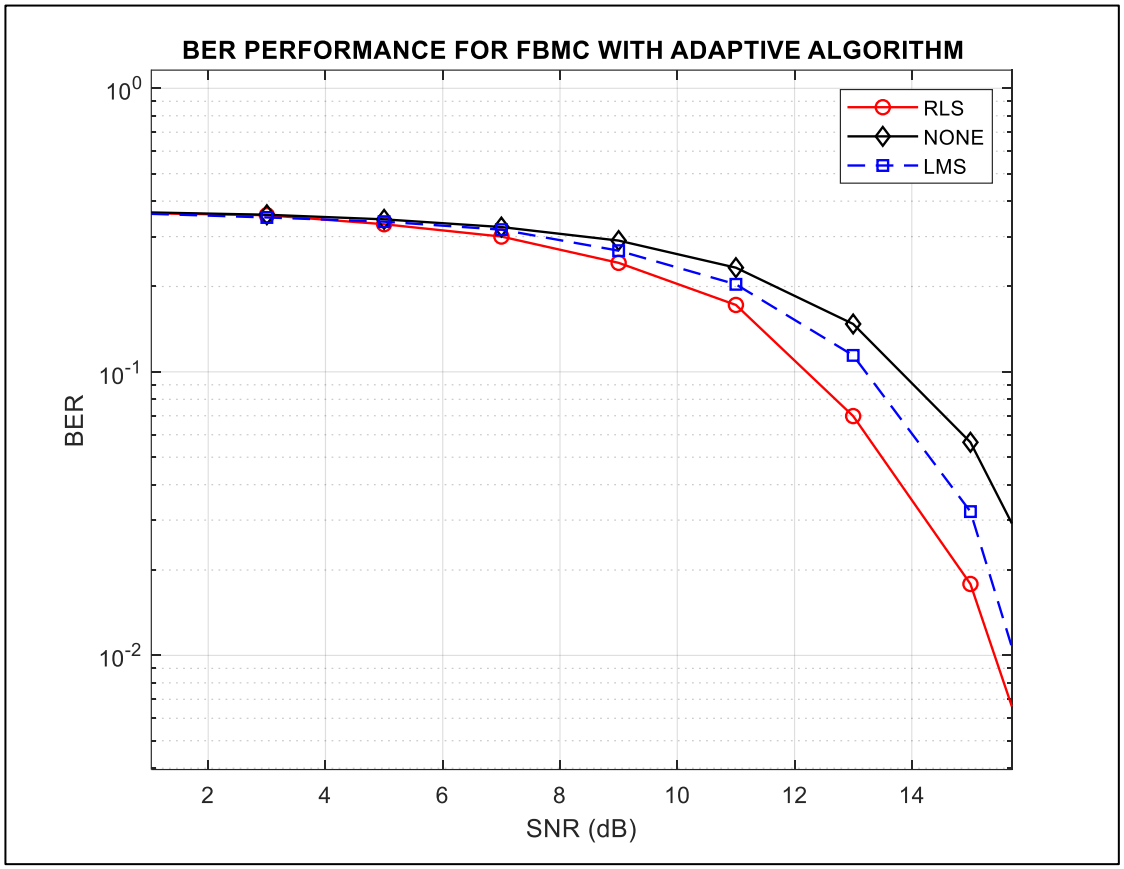

Figure 4.11 Comparison of Adaptive Algorithm For FBMC

Table 4.12
Percentage Improvement Of LMS And RLS

SNR 14 dB		
	BER	Percentage improvement (%)
NONE	0.091	
LMS	0.060	34.06
RLS	0.034	62.63

Figure 4.11 illustrates performance of adaptive algorithm in MIMO FS-FBMC system. The LMS algorithm relies on instantaneous error samples and a fixed step size for coefficient updates based on (2.10). This makes it less effective in environments with strong signal correlation, such as MIMO FBMC systems. Consequently, LMS converges slowly and is unable to sufficiently suppress spatial interference between antennas and intrinsic interference across subcarriers [189]. These limitations result in degraded symbol detection accuracy and higher BER performance. Compared to LMS, RLS algorithm minimizes a least-squares cost function over all past received samples and incorporates the inverse matrix of the input signal. Furthermore, the fast convergence characteristic of RLS allows the equalizer to rapidly adapt to channel variations and frequency-selective fading, which are amplified in MIMO FBMC systems due to the increased channel memory introduced. With 62.63% improvement, RLS achieves more accurate symbol estimation with reduced noise enhancement that lead to lower BER compared to LMS. Although RLS requires more computation due to matrix inversion, this cost is partly reduced in FS-FBMC systems through FFT-based processing and per-subcarrier equalization [141]. As a result, the improved BER performance of RLS in MIMO FS-FBMC systems outweighs its complexity, particularly in high-data-rate and multi-antenna scenarios where LMS cannot effectively suppress intrinsic and spatial interference.

After comparing the performance of different adaptive algorithms, the next subsection evaluates the complexity reduction performance of the variable, inverse and fixed RLS methods.

4.4.6 Computational Complexity Reduction Using RLS

This section presents the BER performance evaluation of the Recursive Least Squares (RLS) algorithm under different complexity reduction approaches which is fixed forgetting factor (FF), variable forgetting factor (VFF) and inverse matrix-based implementation. The objective is to investigate how modifications in the RLS update mechanism influence detection accuracy and computational efficiency within the FS-FBMC system.

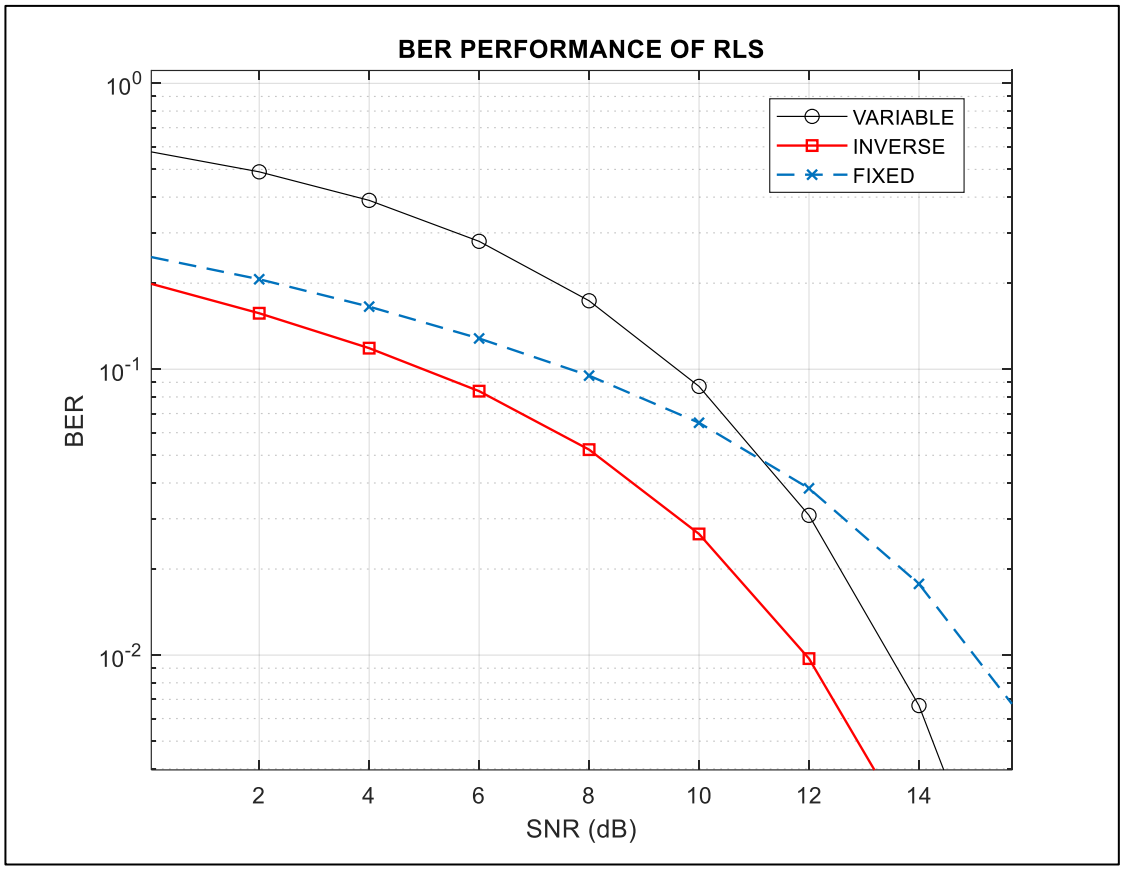

Figure 4.12 Comparison of Reduction Complexity using RLS

Table 4.13
Percentage Improvement Of RLS Performance

SNR 13 dB		
	BER	Percentage improvement (%)
Fixed FF	0.026	
Variable FF	0.014	46.15
Inverse Matrix	0.004	84.61

Figure 4.12 illustrates the BER performance of three RLS based adaptive equalization schemes. The inverse-matrix RLS consistently achieves the lowest BER across all SNR values with 84.61% improvement compared to fixed forgetting factor. This result is expected because the inverse-matrix formulation employs the matrix inversion lemma to recursively update the inverse correlation matrix and preserve conventional RLS algorithm by referring to (3.48). Theoretically, inverse-matrix RLS maintains fast convergence and low steady-state misadjustment resulting in superior BER performance [190]. The fixed forgetting factor (FF) RLS exhibits slightly high BER performance compared to the inverse-matrix approach particularly at moderate to high SNR levels. This behavior is attributed to the fixed memory length imposed by the constant forgetting factor which limits the algorithm ability to adapt optimally under varying channel conditions. If fixed FF value is too large, the algorithm responds slowly to changes and when it too small it may become unstable or overly sensitive to noise. This is why fixed FF suits more in stationary environment. The variable forgetting factor (VFF) RLS demonstrates BER performance with 46.15% improvement comparable to the fixed FF RLS particularly at moderate to high SNR values because variable forgetting factor dynamically adjusts adaptation sensitivity according to channel conditions [191]. As the estimation error decreases, the adaptive forgetting factor converges to its upper bound, causing the VFF-RLS to behave similarly to a fixed FF RLS. This convergence ensures stable operation while maintaining reduced average computational complexity.

4.5 Performance Of BER For 4x4 MIMO FS-FBMC

This section presents the BER performance evaluation of the proposed 4×4 MIMO FS-FBMC system under various receiver and diversity configurations. The analysis includes the impact of Space-Time Block Coding (STBC) to exploit spatial diversity, a comparative study of different equalization techniques and an evaluation of adaptive algorithms including LMS, RLS, and the proposed ECLS method.

4.5.1 Diversity Technique

This section presents the BER performance evaluation of the MIMO FS-FBMC system with and without the application of a diversity technique based on STBC. The objective is to analyze the impact of transmit diversity on detection reliability under fading channel conditions. For system without STBC symbols are transmitted independently across antennas while system with STBC distributes symbols across multiple transmit antennas and time slots to exploit spatial diversity.

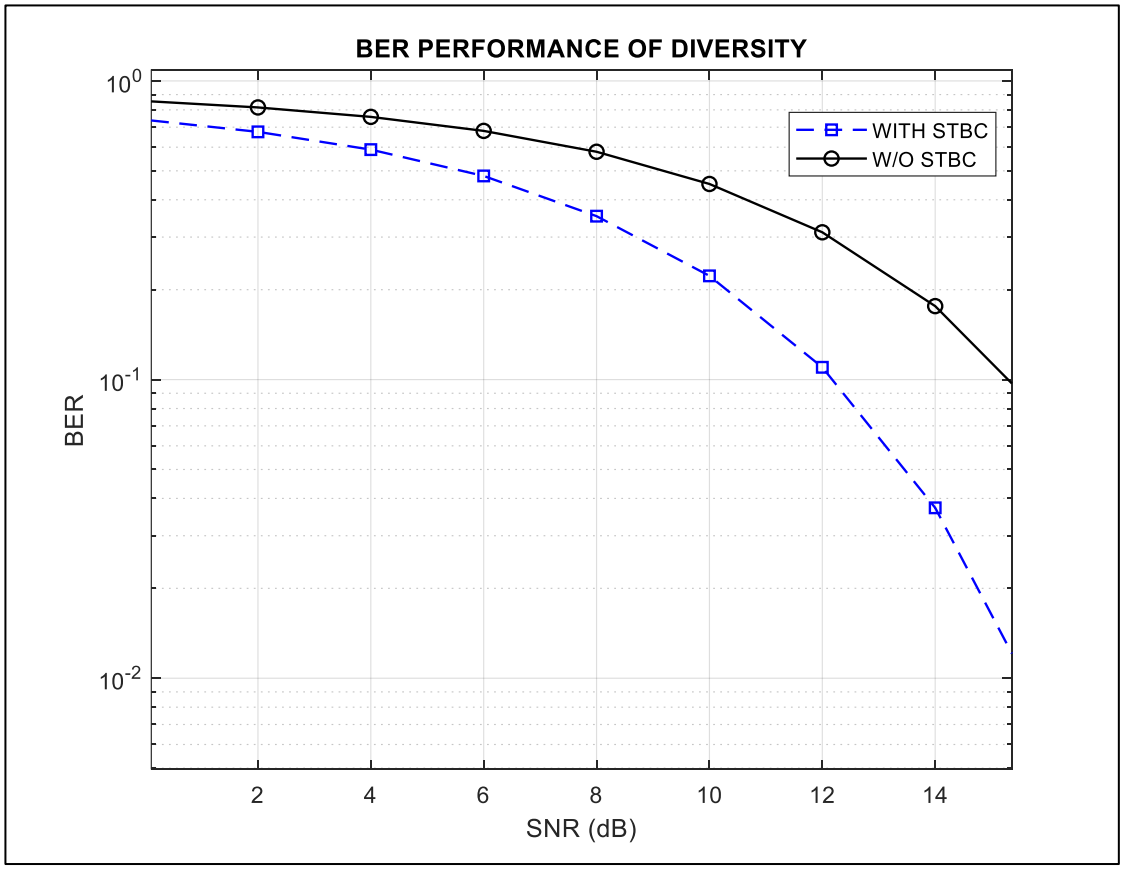

Figure 4.13 Comparison of MIMO FS-FBMC with STBC

Table 4.14
Percentage Improvement Of Diversity

SNR 14 dB		
	BER	Percentage improvement (%)
W/O STBC	0.176	
With STBC	0.037	78

Figure 4.13 shows a significant improvement when ST is applied to the system. The results demonstrate that FBMC with Space–Time coding achieves approximately 78% performance improvement compared to the conventional FBMC system. This improvement is due to the transmit diversity gain provided by ST coding. Previous study has slightly lower BER compared to the proposed MIMO FS-FBMC but come with cost of lower SNR value and single antenna [192].Same information symbol is transmitted across different antennas and time slots referring to (3.25). The equation shows that the transmit data is 4x8 configuration means transmitted 4 unique symbols across 8 time intervals. Spectral efficiency of the system is influenced by the code rate STBC which is ½ based on (2.17) to maximize diversity gain. Application of ST in FBMC will not disturb FBMC structure characteristics. The diversity mechanism significantly reduces the impact of deep fading and noise without sacrificing spectral efficiency. Space Frequency and Space Time Frequency coding schemes cannot be applied to FBMC due to the absence of complex orthogonality and the presence of intrinsic interference caused by OQAM staggering [30]. Lack of orthogonality will affect proper decoding of the system. Therefore, Space Time coding remains the most suitable and effective diversity technique for FBMC systems [158].

After evaluating the BER performance of the 4×4 MIMO FS-FBMC system with and without STBC, the next subsection compares the performance of different equalization techniques

4.5.2 Comparison Type Of Equalizer

This section presents the BER performance evaluation of the MIMO FS-FBMC system using different equalization techniques which is Linear Equalizer (LE) and Decision Feedback Equalizer (DFE). The objective is to analyze the effectiveness of each equalizer in mitigating channel distortion and inter-symbol interference under fading conditions. The comparative analysis highlights the impact of equalizer structure on BER performance and overall system reliability.

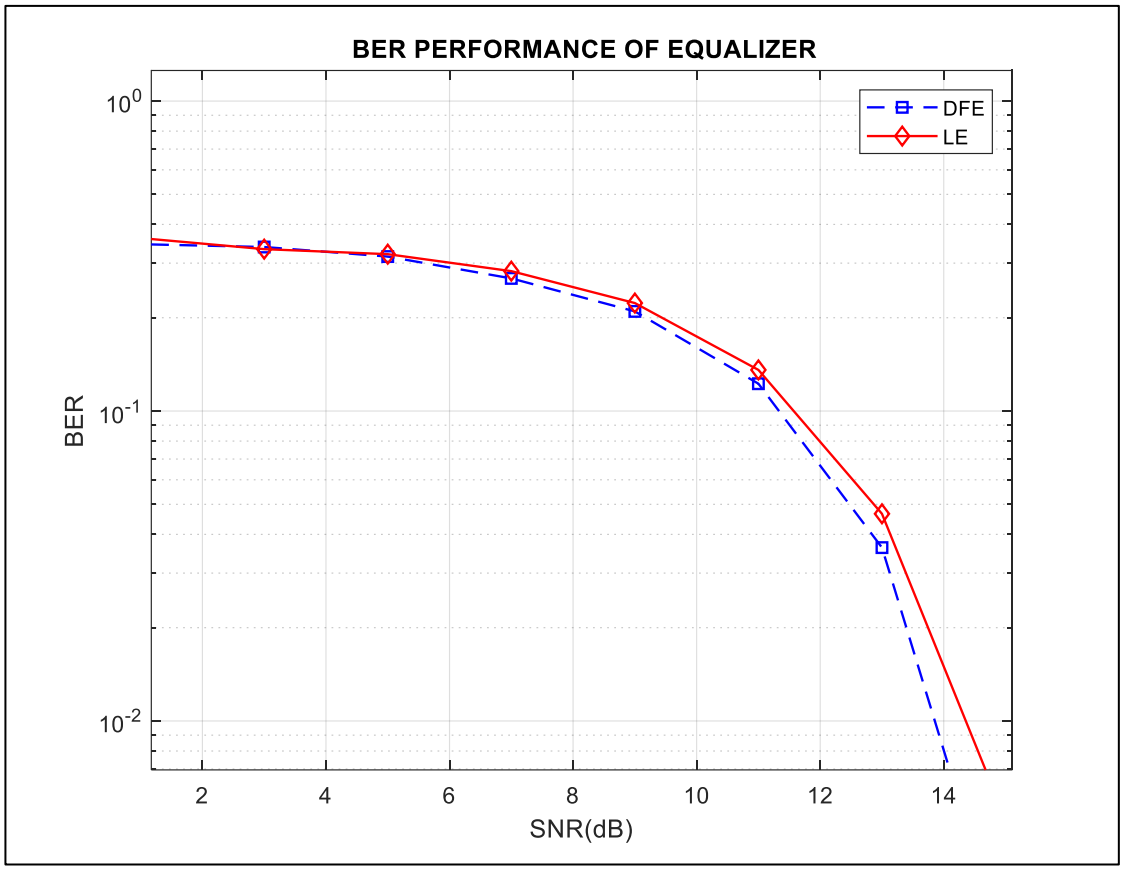

Figure 4.14 Comparison Of Different Type Of Equalizer

Table 4.15
Percentage Improvement Of Equalizer

SNR 14 dB		
	BER	Percentage improvement (%)
LE	0.014	
DFE	0.009	35.71

Figure 4.14 compares performance of BER when applying different types of equalizers. In the MIMO FS-FBMC system, the Decision Feedback Equalizer (DFE) demonstrates a noticeably lower BER with 35.71% improvement compared to the Linear Equalizer (LE) which is consistent with theoretical expectations. FS-FBMC employs long prototype filters and frequency spreading resulting in significant postcursor ISI and intrinsic interference due to OQAM modulation [58] [112]. Linear equalizers treat these interference components as additional noise and rely on channel inversion. It can be seen in (2.14) as weight equalizer coefficient is inversely proportional to channel frequency response thus can lead to noise enhancement particularly in deep fading and high-dimensional MIMO scenarios. Besides that, the linear equalizer overcome channel effects using a single stage filtering. Different with DFE, this nonlinear equalizer exploits past symbol decisions to cancel postcursor interference through its feedback path referring to (3.52). Therefore, DFE is generally expected to outperform linear equalization in scenarios where multipath effects are significant. This process effectively reduces both ISI and spatial interference. This interference cancellation capability reduces noise amplification and improves detection reliability [152]. The performance gap becomes more pronounced as the number of antennas increases, confirming that DFE is better suited for MIMO FS-FBMC systems where channel memory and interference are dominant [193].

After comparing the performance of different equalization techniques, the next subsection evaluates the BER performance of the ECLS, RLS and LMS adaptive algorithms.

4.5.3 Comparison Type Adaptive Algorithm

This section presents the BER performance evaluation of the FS-FBMC system using different adaptive algorithms Least Mean Squares (LMS), Recursive Least Squares (RLS) and the proposed Enhancement Cascaded Least Square (ECLS) method. ECLS is the hybrid of LMS and RLS. The objective is to analyze how different adaptation strategies influence reliability, convergence behaviour and interference mitigation capability under fading channel conditions.

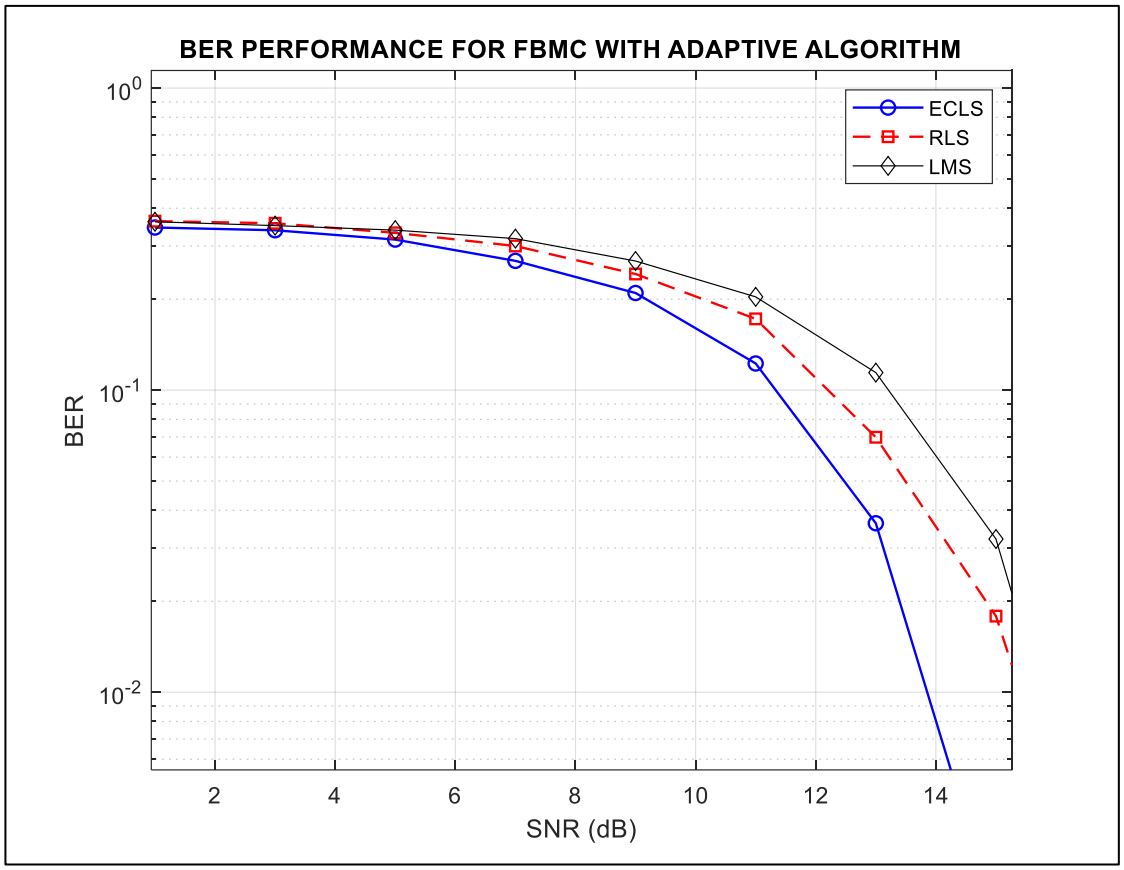

Figure 4.15 Comparison of Different Type Of Algorithm

Table 4.16
Percentage Improvement Of Adaptive Algorithm

SNR 14 dB		
	BER	Percentage improvement (%)
LMS	0.060	
RLS	0.034	43.33
ECLS	0.007	88.33

Figure 4.15 shows performance of adaptive algorithm in MIMO FS-FBMC System. Simulation results indicate that ECLS achieves the lowest BER among the evaluated methods followed by RLS while LMS exhibits comparatively higher BER. The ECLS algorithm achieves superior performance with 88.33% improvement compared to standalone LMS or RLS due to its ability to balance fast convergence and steady-state accuracy. LMS is characterized by low computational complexity and robustness to noise but it converges slowly and suffers from higher residual error [194]. Performance of LMS become worse in channels with strong ISI and time variation. Meanwhile RLS offers rapid convergence and improved tracking capability by incorporating matrix inversion [195]. However it is highly sensitive to noise, numerical instability and increased computational complexity. The proposed ECLS scheme combines the advantages of both algorithms by using LMS first to ensure stable convergence and reduced misadjustment by referring to (3.45). Training rate will help LMS to adapt during initial phase followed by RLS to quickly approach the optimal solution. This adaptive transition allows the hybrid equalizer to efficiently suppress interference while avoiding noise amplification because of RLS operation. This performance trend reflects the ability of ECLS to balance convergence speed and steady-state error leading to more precise symbol recovery in the FS-FBMC system. By referring to value from existing literature that has BER of 0.03 and 0.04 , ECLS successfully validating its suitability for complex MIMO multicarrier environments based on (3.43) [196].

4.6 Performance of JOS AMM ECLS MIMO FS-FBMC

This section presents the integrated performance evaluation of the proposed JOS–AMM–ECLS framework in the 4×4 MIMO FS-FBMC system. The analysis is divided into two main parts. First, the PAPR performance is examined by comparing three configurations which is AMM only, JOS only, and the combined JOS–AMM technique. Second, the BER performance is evaluated under different receiver structures including ECLS, ECLS with DFE and ECLS combined with STBC DFE.

4.6.1 Comparison of PAPR For AMM-JOS

This section presents the PAPR performance analysis of the proposed FS-FBMC system under three configurations AMM only, JOS only and the combined JOS-AMM method. The objective is to evaluate the individual and joint effectiveness of arithmetic complexity reduction and peak suppression techniques in controlling signal amplitude fluctuations.

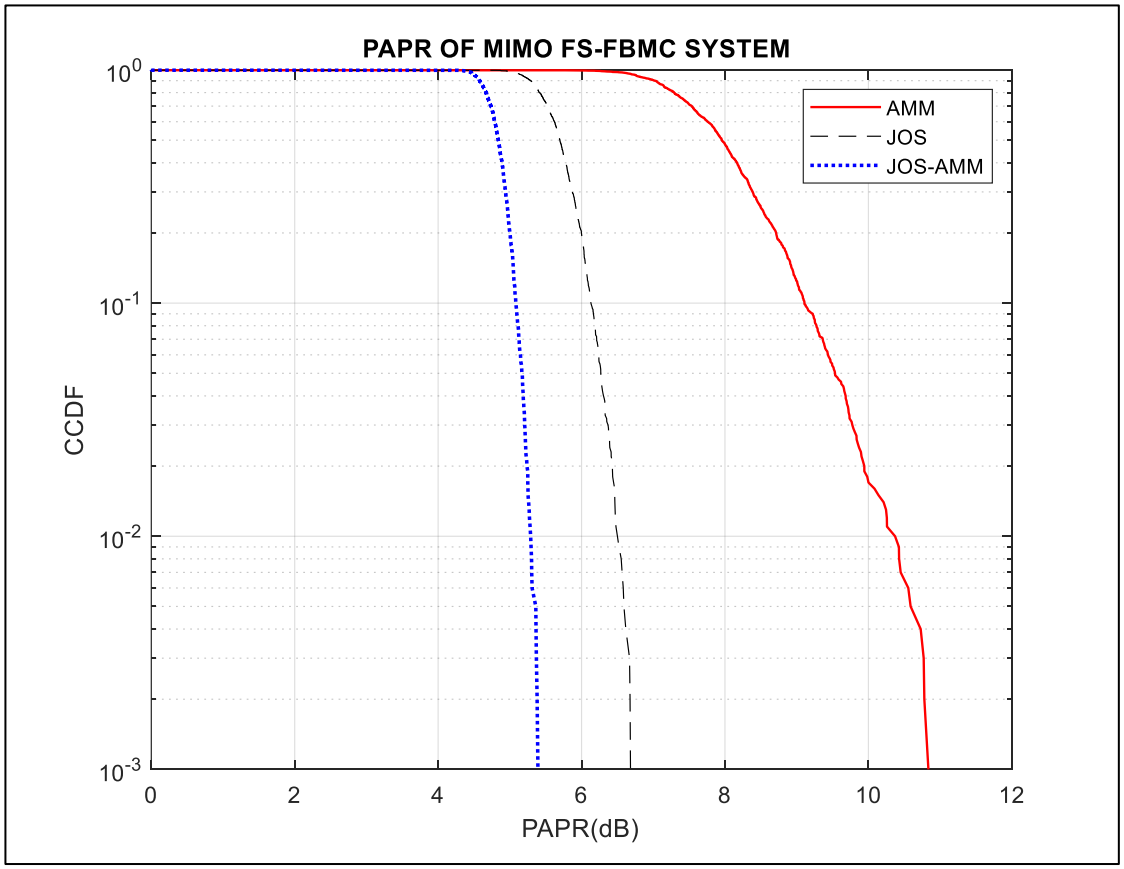

Figure 4.16 PAPR Performance Of AMM JOS MIMO FS-FBMC

Table 4.17
Percentage Improvement Of MIMO FS-FBMC

CCDF Value (10^{-1})		
	PAPR (dB)	Percentage improvement (%)
AMM	9.108	
JOS	6.131	32.68
JOS-AMM	5.083	44.19

Figure 4.16 exhibit the performance of PAPR for MIMO FS-FBMC. The PAPR results indicate that the combined JOS–AMM configuration achieves the lowest PAPR among the evaluated schemes with 44.19 percent improvement, followed by JOS alone with 32.68 percent improvement while AMM alone exhibits comparatively higher PAPR. This performance reflects the distinct functional roles of each technique within the FS-FBMC transmitter structure.

The AMM method is primarily designed to reduce computational complexity by minimizing the number of real multiplications in complex arithmetic operations by referring to (3.19). Although AMM may slightly influence the numerical characteristics of the time-domain signal, it does not explicitly target peak suppression. Therefore, its impact on PAPR reduction is limited. The observed PAPR improvement under AMM is mainly attributed to minor arithmetic reshaping effects rather than full amplitude control.

Different with other technique, the Joint Optimization System (JOS) which is hybrid of clipping and μ-Law is specifically developed to mitigate high amplitude peaks in the transmitted waveform referring to (3.32). By optimizing signal characteristics prior to transmission, JOS effectively reduces extreme amplitude fluctuations caused by the constructive superposition of multiple subcarriers in the FS-FBMC system. Since PAPR is directly related to the maximum instantaneous power and relate to the average power thus any technique that actively controls peak growth will produce significant improvement [76]. This explains why JOS outperforms AMM in PAPR reduction.

The best performance of the combined JOS–AMM configuration demonstrates a complementary effect between peak suppression and arithmetic restructuring. JOS directly minimizes high-amplitude components, while AMM enhances numerical stability and potentially reduces minor amplitude variations through optimized computation. When integrated, JOS controls the dominant peaks and AMM maintains efficient signal formation, resulting in a more balanced amplitude distribution. The

probability of extreme peak occurrence is further reduced leading to the lowest PAPR among the tested configurations. These findings confirm that direct peak optimization mechanisms such as JOS have a more impact on PAPR reduction compared to purely computational optimization methods. However, integrating both techniques provides enhanced overall performance by simultaneously improving power efficiency and computational complexity within the MIMO FS-FBMC system.

After evaluating the PAPR performance of AMM, JOS and the combined AMM–JOS method, the next subsection examines the BER performance of the proposed ECLS based MIMO FS-FBMC system.

4.6.2 Comparison Of BER For ECLS

This section presents the BER performance evaluation of the proposed MIMO FS-FBMC system using three receiver configurations ECLS, ECLS with DFE and ECLS combined with STBC-DFE. The objective is to examine how adaptive equalization, interference cancellation, and spatial diversity jointly influence detection reliability under fading channel conditions.

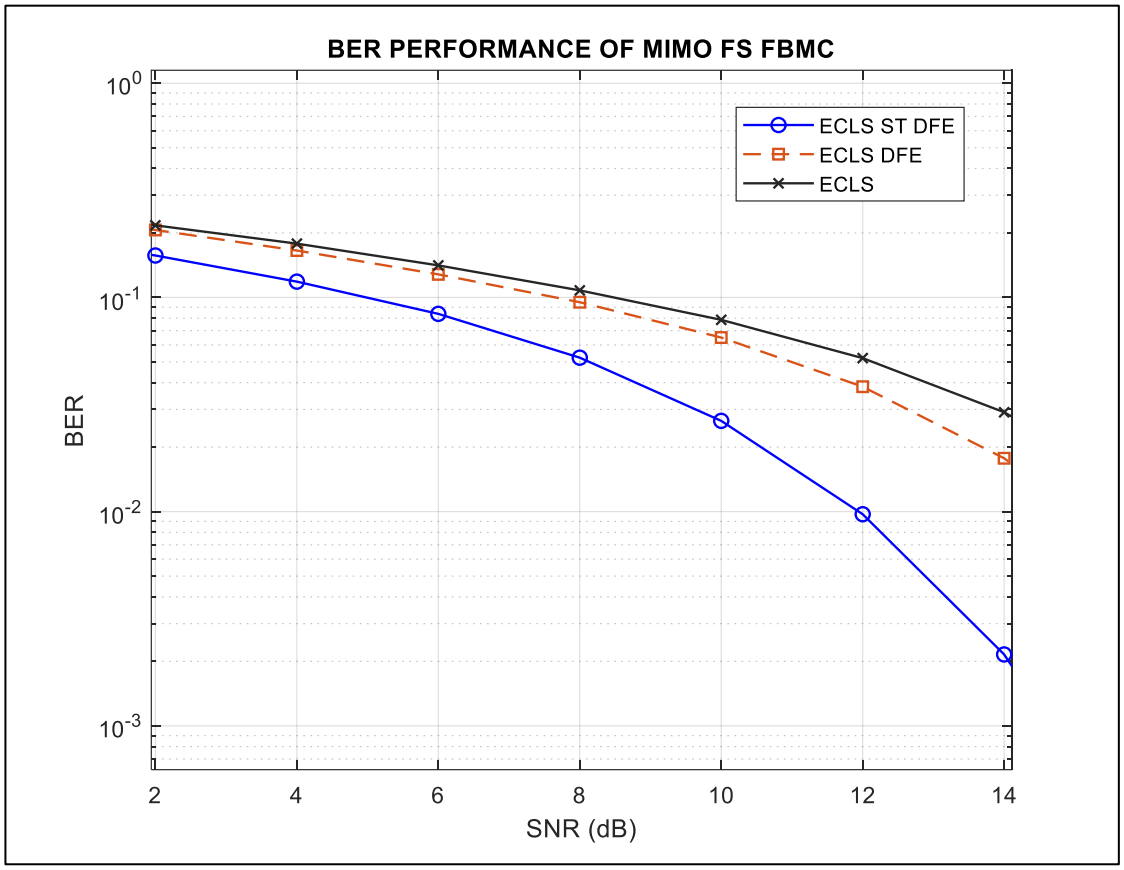

Figure 4.17 Comparison Of System Performance

Table 4.18
Percentage Improvement Of MIMO FS-FBMC

SNR 14 dB		
	BER	Percentage improvement (%)
ECLS	0.029	
ECLS DFE	0.018	37.93
ST ECLS DFE	0.002	93.10

Figure 4.17 show the outcome of the comparison of MIMO FS-FBMC system. The ECLS equalizer alone exhibits the poorest performance due to its linear structure, which is insufficient to fully mitigate intersymbol interference in frequency-selective FBMC channels. Incorporating a decision feedback equalizer significantly improves performance with 37.93% improvement by effectively cancelling post-cursor ISI and reducing noise enhancement by referring to (3.52). The best performance is achieved when the ECLS scheme is combined with space time DFE with 93.10% improvement which exploits spatial diversity and jointly mitigates temporal and antenna interference [150]. This hierarchical improvement confirms the theoretical advantage of nonlinear and space time equalization in MIMO-FBMC systems. The progressive BER improvement is due to the effective utilization of training sequences and RLS matrix inversion as the equalizer structure evolves from linear to decision feedback and space–time processing referring to (3.50) . While matrix inversion enables fast convergence in all cases, the enhanced structural capability in DFE and ST-DFE allows the estimated coefficients to suppress interference more effectively, resulting in better performance [112][158].

After evaluating the BER performance of the proposed ECLS based system, the next subsection compares the overall BER performance using different numbers of antennas.

4.6.3 Comparison Of BER Using Different Number Of Antenna

This section presents the integrated performance evaluation of the proposed AMM–JOS–ECLS based ST-MIMO FS-FBMC system. The objective is to investigate the combined impact of computational complexity reduction (AMM), PAPR minimization (JOS), and adaptive equalization (ECLS) under different spatial configurations. To provide a comprehensive analysis, BER performance is simulated for SISO (1×1), 2×2 MIMO, and 4×4 MIMO scenarios.

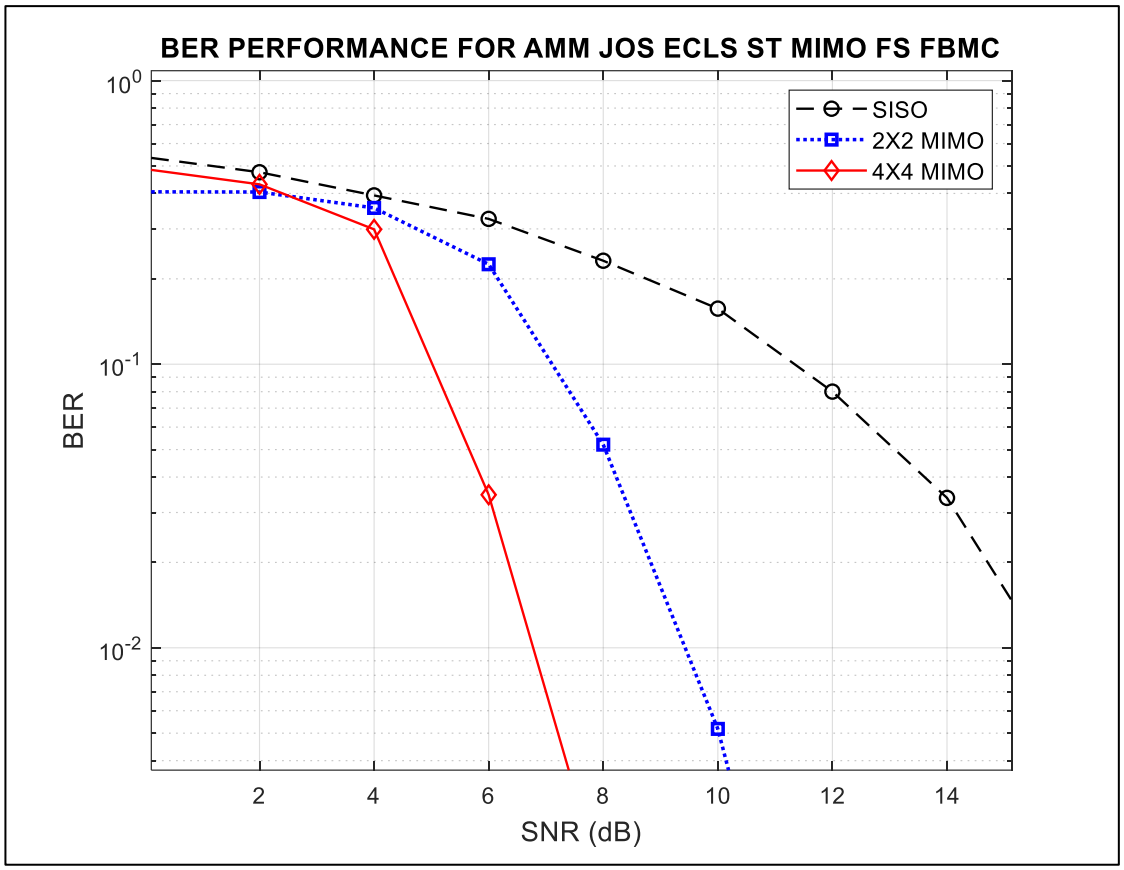

Figure 4.18 Comparison Different Number of Antenna

Table 4.19
Percentage Improvement Of Different Number Of Antenna

SNR 7 dB		
	BER	Percentage improvement (%)
SISO	0.276	
2X2 MIMO	0.107	61.23
4X4 MIMO	0.007	97.46

Figure 4.18 above presents the BER performance comparison of the proposed AMM–JOS–ECLS based ST-MIMO FS-FBMC system under SISO (1×1), 2×2, and 4×4 configurations. As expected, the 4×4 MIMO system achieves the lowest BER with 97.46% improvement, followed by the 2×2 configuration with 61.23% improvement while the SISO system exhibits the highest BER. This performance aligns with spatial diversity theory where the achievable diversity order increases with the product of transmit and receive antennas (Nt x Nr) [158]. The 4×4 system therefore provides the highest diversity gain and strongest resistance against multipath fading.

The simulation results shows that BER curves appear simultaneously in the lower SNR region around 7 dB while the SISO curve still extends until around 14 dB

consistent with the previous section results. This behavior indicates that the SISO baseline model remains unchanged and correctly normalized. The apparent leftward shift of the MIMO curves is not due to SNR scaling error, but rather due to the diversity gain introduced by STBC and multiple receive antennas because this system achieve ½ code rate [197].

In MIMO transmission, each transmitted symbol experiences multiple independent fading paths. At the receiver, these replicas are combined constructively through STBC decoding and ECLS equalization. This spatial combining effectively increases the received signal reliability without increasing transmit power [142] [198]. As a result, the MIMO systems achieve lower BER at lower SNR values compared to SISO. Therefore, while SISO requires 14 dB to achieve a specific BER threshold, the 2×2 and 4×4 systems can achieve similar or better BER at much lower SNR levels.

The BER curves around 7 dB reflects the transition region where diversity gain becomes significant. Beyond this point, the slope of the 4×4 curve becomes steeper than 2×2 and SISO indicating a higher diversity order. This confirms that the proposed ST-MIMO FS-FBMC framework successfully exploits spatial diversity and that performance improvement is not merely due to power increase but due to diversity combining and improved channel conditioning via ECLS.

Overall, the results validate that increasing the antenna configuration significantly enhances BER performance with 4×4 achieving the best reliability followed by 2×2 while SISO remains the least robust under fading conditions.

4.7 Summary

Overall, the results confirm that the proposed integrated JOS–AMM–ECLS MIMO FS-FBMC framework simultaneously addresses the three major bottlenecks of multicarrier systems by reducing PAPR, shortening processing time hence reduce complexity and improving BER performance. This combined improvement demonstrates the framework's potential to support more power-efficient, computationally efficient and reliable wireless communication systems for future performance 5G applications and beyond.

CHAPTER 5
CONCLUSION AND FUTURE DEVELOPMENT

5.1 Conclusion

This research presented a comprehensive performance improvement framework for a MIMO FS-FBMC system by jointly addressing three major challenges in multicarrier transmission. The first one is high PAPR, computational complexity, and ISI with BER degradation. A cascaded clipping and μ-law companding technique name Joint Optimization System (JOS) was applied at the transmitter to reduce PAPR. The method effectively improved power efficiency without causing severe signal distortion.

Additional Multiplication Method (AMM) with 3 addition and 3 multiplications was employed to reduce computational complexity. The results show that AMM significantly lowers the number of arithmetic operations required for signal processing while maintaining acceptable system performance because conventional multipliers lead to excessive hardware cost and power consumption.

Furthermore, to mitigate ISI and improve BER performance, a hybrid LMS–RLS called ECLS adaptive equalization scheme was introduced at the receiver. Simulation results verified that the ECLS scheme achieves improved BER performance compared to standalone LMS and RLS methods while simultaneously reducing computational complexity.

From a practical and commercial perspective, the proposed framework can support wireless systems with lower power use, faster processing time and more reliable transmission. These benefits make it suitable for future 5G and beyond applications such as IoT, smart transportation and industrial automation.

Overall, the proposed MIMO FS-FBMC system with JOS, AMM and ECLS equalization demonstrates a balanced trade-off between PAPR reduction with 44.19% improvement, computational efficiency with 10.49% improvement and reliable system with 93.10% improvement performance. These results highlight the effectiveness of the proposed techniques for practical high-data-rate and energy efficient wireless communication systems.

5.2 Future Development

Future research may explore the integration of advanced diversity and coding techniques, such as higher-order space–time coding or low density parity check (LDPC) based channel coding, to improve reliability under severe fading conditions. In addition, adaptation methods for the ECLS algorithm including variable parameter tuning may further improve convergence speed and tracking performance in time-varying environments. Practical implementation aspects should be investigated through hardware-oriented analysis including field programmble gate array (FPGA) validation, power consumption measurement and fixed-point precision studies to assess real-time feasibility. Extended performance evaluation under realistic channel models, high mobility scenarios and imperfect channel state information (CSI) conditions would strengthen system robustness assessment. The proposed framework may also be expanded toward massive MIMO configurations to align with emerging 5G-Advanced and 6G communication requirements.

In order to achieve these directions, the first milestone is to convert the MATLAB algorithms into fixed point form and evaluate memory usage, processing delay, power consumption and hardware resource requirements. The second milestone is to validate the transmitter and receiver through real-time testing under different mobility and multipath conditions. These steps would support its deployment in low-power IoT devices, industrial automation and low-latency wireless systems.

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