PHASE LINEAR REGRESSION MODEL WITH ADAPTIVE MODULATION TECHNIQUE FOR FILTERED-ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING

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DEDICATION

Perseverance, a word that I always keep that word in my heart and my mind. The journey that seems like the never-ending story has come to the end, at least for this thesis. Indeed, at every hardship came ease. In this thesis, I am fully dedicated to my parents that as usually keep supporting me until the end. Finally, to my both supervisors; Dr. Rudzidatul Akmam Dziyauddin and Dr.Marwan Hadri Azmi, thank you for everything.

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ABSTRACT

One of the applications of Orthogonal Frequency Division Multiplexing (OFDM) is teleconferencing as it has shown to have ten times better downlink response time compared to 3G. Despite the robustness against multi-path fading and ease of OFDM implementation, OFDM still suffers from high sidelobes in frequency domain and high Bit Error Rate (BER). In the OFDM system, frequency mask regulation is adopted to overcome the issues, whereby a portion from both ends of the bandwidth is reserved as a frequency guard band. This thus degrades the spectral efficiency and does not reduce the Out of Band Emission. Therefore, the goals of this research are to investigate the impact of filter types, and design a new filter in the filtered-OFDM (f-OFDM) system. Initially, several Infinite Impulse Response (IIR): Butterworth, Chebyshev, Elliptic; and Finite Impulse Response (FIR): Equiripple, Bohman, and Hamming filters were evaluated in terms of magnitude response, phase response and group delay. The results showed that Elliptic and Butterworth achieved good performance in magnitude response and phase response for FIR and IIR, respectively. The Equirriple was applied by varying the filter order in f-OFDM under different modulation schemes and channel models. It was found that f-OFDM achieved BER 10^{-6} at 11.9 dB while OFDM 12.4 dB, particularly when Equiripple with 512th order was used. However, the complexity and group delay also increased. By using the results of the BER performance for the optimum Equiripple design in the f-OFDM, the link adaptation model was proposed. Next, because IIR is a non-linear phase filter, a new method called Phase Linear Regression Model, a combination of mean square error and best fit was proposed by considering the magnitude and phase responses in designing Butterworth for the f-OFDM waveform. The new IIR design with 5th order achieved BER 6.667×10^{-7} at SNR 12 dB, while Equirriple filter 1.552×10^{-5} at the same SNR and filter order for the Quadrature Phase Shift Keying modulation. In conclusion, the feasible type of IIR (Butterworth) and FIR filter (Equiripple) can improve the BER performance for the f-OFDM system compared with OFDM. The findings on the link adaption model as well as the new IIR filter should be further investigated for the multi-cell f-OFDM system

ABSTRAK

Salah satu daripada aplikasi yang mengunakan Pemultipleksan Bahagian Frekuensi Ortogon (OFDM) adalah telesidang yang mempunyai sepuluh kali ganda tindak balas masa pautan lebih baik berbanding 3G. Walaupun OFDM mempunyai kelebihan terhadap pelbagai laluan dan kemudahan pelaksanaan, ia masih mempunyai kekurangan, termasuklah sisi cuping dan Kadar Ralat Bit (BER) yang tinggi. Di dalam sistem OFDM, pengawalan topeng kekerapan digunakan untuk mengatasi masalah cuping sisi tinggi dan kesilapan BER, yang kedua-dua hujung jalur lebar dikhaskan sebagai penjaga jalur frekuensi. Ini dapat mengurangkan kecekapan spektrum tetapi tidak mengurangkan emisi jalur luar. Oleh itu, penyelidikan ini menyiasat kesan jenis penapis dan juga mereka bentuk penapis dalam sistem penapisan-OFDM (f-OFDM). Beberapa Tindak Balas Dorongan Infiniti (IIR): Butterworth, Chebyshev, dan Elliptic; dan Tindak Balas Dorongan Finiti (FIR): Equiripple, Bohman, dan penapis Hamming, dinilai dari segi tindak balas magnitud, tindak balas fasa dan kelewatan kumpulan. Keputusan menunjukkan Elliptic dan Butterworth mencapai prestasi tindak balas magnitud dan tindak balas fasa yang baik bagi FIR and IIR. Equirriple digunakan dengan mengubah aturan penapis dalam f-OFDM untuk modulasi dan juga model saluran berbeza. Didapati f-OFDM mencapai BER 10^{-6} pada 11.9 dB manakala OFDM 12.4 dB, khususnya dengan mengunakan aturan ke-512. Walaupun begitu, kadar kerumitan dan kelewatan kumpulan meningkat. Dengan mengunakan keputusan prestasi BER, untuk rekaan tapisan Equirriple optimum dalam f-OFDM, adaptasi pautan dicadangkan. Berikutnya, disebabkan IIR tidak mempunyai fasa tapisan lelurus, kaedah baru yang diberi nama Model Fasa Lelurus Regresi diperkenalkan dengan mengunakan kombinasi ralat punca kuasa dua dan kesesuaian terbaik yang mengunakan magnitud dan fasa tindak balas sebagai pengiraan untuk membina tapisan Butterworth terbaik untuk gelombang f-OFDM. Rekaan IIR terbaru aturan ke-5 yang dihasilkan mampu mendapatkan BER 6.667×10^{-7} di SNR 12 dB, manakala tapisan Equirriple hanya mendapatkan 1.552×10^{-5} pada SNR yang sama untuk modulasi penguncian anjakan fasa kuadratur. Kesimpulannya, kebolehgunaan jenis tapisan IIR (Butterworth) dan tapisan FIR (Equirriple) mampu meningkatkan prestasi BER untuk sistem f-OFDM berbanding sistem OFDM. Hasil kajian dari model adaptasi pautan dan juga tapisan IIR yang baru boleh dilanjutkan dengan lebih mendalam untuk beberapa-sel f-OFDM.

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LIST OF ABBREVIATIONS

AI	-	Artificial Intelligence
APF	-	All pass filter
BER	-	Bit Error Rate
CP	-	Cyclic Prefix
CQI	-	Channel Quality Information
CSI-RS	-	channel state information - reference signal
CSIR	-	Channel State Information
D/A	-	Digital-to-Analogue
DPSS	-	Discrete Prolate Spheroidal Sequence
eMBB	-	Enhance Mobile Broadband
FB	-	Fractional Derivative
FBMC	-	Filter Bank Multi-Carrier
FFT	-	Fast Fourier Transform
FIR	-	Finite Impulse Response
f-OFDM	-	Filtered Orthogonal Frequency Division Multiplexing
FPBF	-	Fractional Power Binomial Filter
GFDM	-	Generalised Frequency Division Multiplexing
HARQ	-	Hybrid Automatic Repeat Request
ICI	-	Intercarrier Interference
Ifft	-	Inverse Fast Fourier Transform
IIR	-	Infinite Impulse Response
IoT	-	Internet of Thing
IR 4.0	-	Industrial Revolution 4.0
ISI	-	Intersymbol Interference
ITU-R	-	International Telecommunication Union – Radiocommunication Sector
MAS	-	Multiple Access Scheme

MCS	-	Modulation and Coding Scheme
MIMO		Multiple Input Multiple Output
mMTC	-	Massive Machine Type Communication
MOTLBO	-	Multi-objective Teaching Learning Based Objective
MR-FDPF	-	Multi-Resolution Frequency Domain ParFlow
MSE	-	Mean Square Error
OFDM	-	Orthogonal Frequency Division Multiplexing
OOBE	-	Out-of-Band Emission
OQAM	-	Offset Quadrature Amplitude Modulation
PB-LA	-	Probability-Based Link Adaptation
PMLR	-	Phase Magnitude Linear Regression
RAN	-	Radio Access Network
RU	-	Resource Unit
RRC	-	Root-Raised-Cosine
SB-LA	-	State-Based Link Adaptation
SMT	-	Staggered Multi Tone
SNR	-	Signal Noise Ratio
UFMC	-	Universal Filter Multi-Carrier
URLLC	-	Ultra Reliable Low Latency Communication
4G	-	4th Generation Communication
5G	-	5th Generation Communication
6G	-	6th Generation Communication

LISTS OF SYMBOLS

$\in$ - Subset

α - alpha

ω - omega

ξ - zeta / selective factor

π - pie

Δ - delta

y - y-axis

X - x-axis

y_d - y difference

y_{lsi} - y point least square

Σ - Total summation

m - slope

c - Intercept y-axis

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background

The increasing integration of the Internet of Everything in the industrial value chain has demanded an industrial revolution called Industry 4.0 (IR 4.0) [1]. The idea of smart factories is that machines are augmented with web connectivity and stay connected to a system that can visualise the entire production chain and make decisions on its own via artificial intelligence (AI). The trend is towards automation and data exchange in manufacturing technologies, which involves the Internet of Things (IoT), Industrial Internet of Things (IIoT), cloud computing and cognitive computing [1-2]. IR 4.0 is an enabler for communication between people, machines and resources. Cisco estimated that IoT will introduce 50 billion connected devices to the Internet in 2020 [3]. Nokia Corporation, on the other hand, has gathered information from the market in 2010 which showed the growth of 10,000 times more traffic for all mobile broadband technologies between 2020 and 2030 [4].

The current fourth generation (4G) cellular networks support remarkable features such as teleconferencing, wider bandwidths, higher data rate, entirely packet-switch networks, high mobility communication of 12.5 Mbps and ten times better downlink response time than the 3G network [5]. However, such features can no longer support the exponential wireless traffic demand [6]. Research centres, universities and industries are aggressively working towards the evolution of wireless communication, named fifth generation (5G) technology, that can cater to IoT and IR 4.0. The 5G technology is anticipated to be commercially launched in 2020, however as the pandemic Covid-19 hit nationwide in early 2020, the rollout of 5G in the entire globe is delayed [1-4]. The two main 5G visions, which are the 10 Gbps spectral efficiency and latency as low as 1 ms [7], are crucial for IR 4.0 and IoT.

Since the past several decades, researchers have been developing a new generation of mobile wireless by adopting the latest physical waveforms or innovative multiple access schemes (MAS) to improve spectrum efficiency as well as other features. In the early stage of 5G network development, it was hard to predict the 5G channel model since the plan and design are much more challenging. Among the studied waveform candidates for 5G systems are Filter-Bank Multi-Carrier (FBMC) [8], Universal-Filtered Multi-Carrier (UFMC) [9], Filtered Orthogonal frequency-division multiplexing (F-OFDM) [10] and Generalised Frequency Division Multiplexing (GFDM) [11].

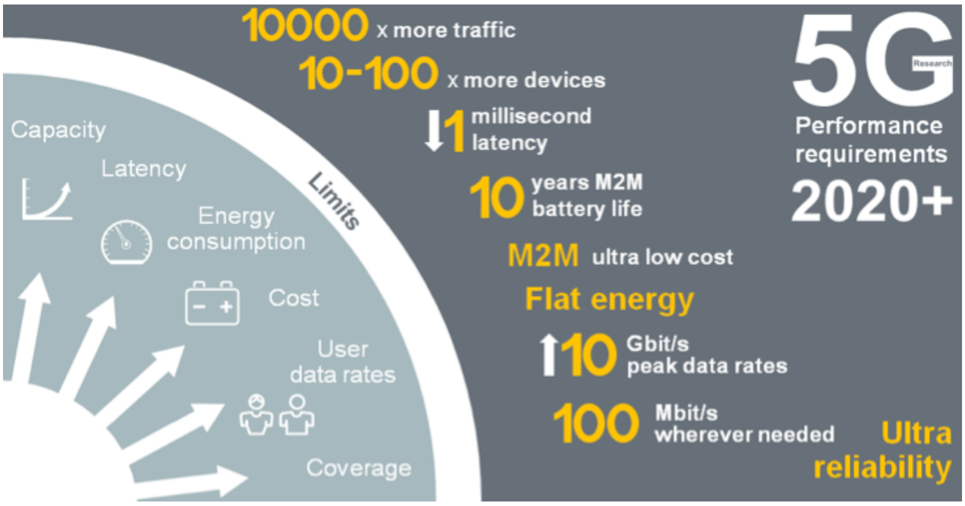

Figure 1.1 5G Performance requirements [12]

Figure 1.1 shows the performance requirements for standard 5G by the International Telecommunication Union Radiocommunication Sector (ITU-R) [12].

1.2 Problem Statement

In 4G radio access network (RAN), the Orthogonal Frequency-Division Multiplexing (OFDM) waveforms have taken place to determine the connection that fits the 4G standard protocol [13]. Despite the fact that 4G can achieve data rates up to 1 Gbps for low mobile applications and 100 Mbps for high mobile applications, it also suffers from several limitations [14-15]. Specifically, the path from a transmitting to a receiving end somehow encounters delay spread in the time domain. As a result, the OFDM symbol is spread out and interferes with the following symbols [16-17]. This is referred to as ISI, which is illustrated in Figure 1.2. To mitigate ISI, the OFDM introduced CP to eliminate ISI from the previous symbol as guard interval [18]. At the frequency domain, the carriers in the bandwidth also suffer from delay spread while sending data thru multipath which leads to loss of orthogonality and resulting high BER at receiver because each carrier carried a set of data [19-20]. Hence, the filter can be employed in shaping the data signal so that OOBE and carriers overlapping can be reduced resulting to low BER [21].

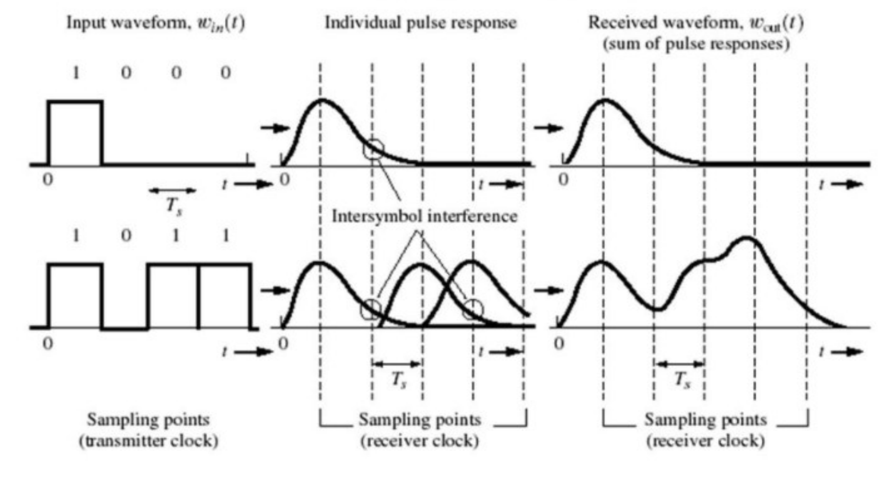

Figure 1.2 Intersymbol interference in waveform [18]

To date, with the goal of having stronger MAS schemes for 5G RAN, new OFDM-based MAS platforms have been developed by studying the limitations of the 4G OFDM waveforms [22]. One of them is f-OFDM, which is the focus of this research. These new waveforms will be more robust against the time frequency synchronisation problem. They have the potential of mixing different traffic specifications and supporting the scenarios of spectrum fragmentation due to the improvement in the localisation of the spectrum compared to other 5G MAS candidates [23].

In f-OFDM, a filter is applied to the time domain of the OFDM symbol to improve out of band radiation of the sub-band signal, while the orthogonality of the OFDM symbols is simultaneously maintained [24]. The primary function of the filter is to preserve the actual data from being altered, and the purpose is to further increase the efficiency of the spectrum in digital communication [25]. With the filter, the band signals can be effectively suppressed, which reduces out-of-band emissions [26]. The filters are selected due to their unique filtering techniques and varied properties which can suppress side lobes and minimise the transition region [21]. By combining the CP of OFDM with a filter, the f-OFDM waveform can achieve a desirable frequency localisation for bandwidths as narrow as a few tens of subcarriers, while maintaining the ISI within an acceptable limit [27]. Therefore, filter design and good specifications are essential for enhancing the data rate, as required by the 5G standard.

Most researchers commonly employ FIR filters such as rectangular windows, Triangular windows, Hanning windows, Hamming windows and Blackman windows [28], which require high filter order to attain the desired parameter. Most of significant works are unable to reach bit-error-rate (BER) of 10^{-6}, which is the standard of QoS of video buffed streaming, Transmission Control Protocol (TCP) based application (e.g. world wide web, file transfer protocol and peer-to-peer file sharing) and critical delay sensitive signal for 5G mobile communication[29]. By using Reed-Solomon, the BER performance for 256 QAM was analysed up to 10^{-4} and the filter order tested was very high (512th order), making the system more complex and the performances is insignificant compared to the other filters simulated [30]. On the one hand, the authors in [31] used Nuttall's Blackman-Harris window with the 512th order and were only able to demonstrate the BER of up to 10^{-3}. Besides the filter design, the appropriate modulation scheme is also vital for increasing the spectral efficiency. This can be solved by link adaptation. However, significant works found regarding the OFDM system [32-34] have not dealt with link adaptation in f-OFDM. Moreover, previous FIR studies did not include the link adaptation model. Although the filter consists of FIR and IIR, far too little attention has been paid to IIR in f-OFDM. In fact, most previous IIR works [35-37] were not implemented in the mobile communication system, even in simulations system because of non-linear phase and its poles and zeros complexity. The advantage of IIR is low filter order required for similar performance in FIR. Therefore, it will be interesting to employ IIR with a new design in f-OFDM.

1.3 Research Objectives

The research aims to design the best FIR and IIR designs for f-OFDM that can achieve the BER of 10^{-6} with a minimum filter order. To achieve this aim, three specific research objectives are presented as follows:

(a) To propose a new IIR design technique using magnitude, phase and group delay parameters

(b) To simulate and evaluate a new IIR design technique for f-OFDM based on BER and Mean Square Error (MSE) performance

(c) To validate the new IIR design with existing FIR filter for f-OFDM subject to BER performance

1.4 Scope and Limitation of Work

The scope of study in are divided into three main areas, which are filtering, multiplexing/multiple access and modulation technique. The research is conducted based on simulation works using MATLAB. The simulation performances of FIR filters, namely, Equiripple, Bohman, Hamming while theIIR filters such as Butterworth, Chebyshev and Elliptic, are extensively studied in terms of magnitude response, phase response, group delay as well as minimum filter order and nearly ideal filter responses. The maximum filter order for FIR and IIR are 512th and 30th orders, respectively. The reason why the filter is limited to such orders is because there is no significant roll-off of transition region after a few increments.

In this simulation work, the mobile communication assumed is point-to-point f-OFDM in AWGN channel model and Rician channel model. The simulator employs QPSK, 64QAM, 128QAM and 256QAM for all FIR cases because of the 5G standard, while QPSK is solely selected for IIR due to the complexity of filter coefficient. The higher the modulation, the higher the throughput is, but prone to error. This is because for a low modulation scheme like QPSK represented 2 bits per symbol in a single carrier might achieve low ISI and BER leading to a robust communication, but low throughput. Meanwhile the higher modulation like 256QAM representing 8 bits per symbols may increase the ISI, but can carry more data per symbol resulting to high throughput. For QPSK, low transmit power is sufficient to transmit the data and normally suitable for the MS at edge networks. This contrasts with the higher modulation as high transmit power is required as often for the MS near to the BS.

Since the focus is on the filtering technique, the limit of the work is to uncoded simulation so that the complexity is not increased. In addition to that, a coded simulation is not straightforward simulation, as the encoder involves hard- and soft-encoder. For the range of SNR chosen in the study is -5dB to 45dB due to the common practises found for the 5G performance evaluation and in wireless communication 40dB is consider excellent signal. All BER performance in this work are compared with OFDM as a validation.

1.5 Significance of the Study

Since most previous works only examined a few filter characteristics, the present research includes an extensive evaluation such as magnitude response, phase response, group delay and minimum filter order. The filter responses with different filter orders that are feasible to increase the performance of the f-OFDM system are specifically investigated for both FIR and IIR. The study determines the IIR and FIR parameters with the best filter order that can achieve optimum BER performance and has low complexity. The optimum FIR design demonstrated the BER performance of 10^{-6} under several modulations.

Based on the results of group delay, implementation cost and BER of 10^{-6} of each FIR design a new Link-Adaptation Model for f-OFDM using optimum FIR is proposed. The Link-Adaptation Model consists of entry and exit SNR thresholds as a reference for the BS to decide which modulation is the optimum to be employed for data transmission to the MS. The significant of 5G link adaptation model in the current work l can be used in the actual mobile communication system for selecting the adaptive modulation scheme by considering the radio link condition, which is SNR Although the work does not assume the coding rate, the link adaptation model can still be used to validate the respective modulation and coding rate whether fall between the proposed exit and entry SNR thresholds. Figure 1.3 show that Coding rate gain for uncoded BPSK, the proposed link adaption results can be extended to the specific coded system by knowing the type of code and its coding gain. In other words, the BER performances of proposed link adaption model will be moved to the left by the value of the coding gain. Changing the channel code will give different coding gain that will change proposed link adaption model accordingly [38].

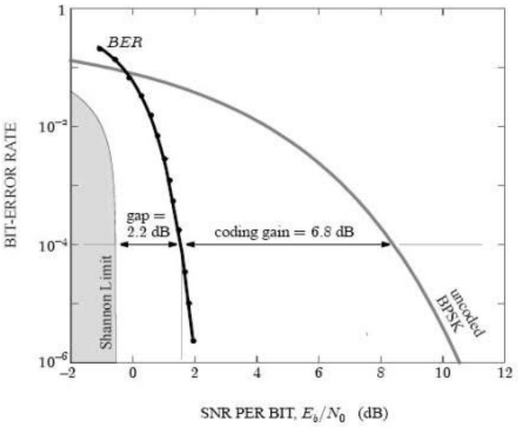

Figure 1.3 Coding gain for uncoded BPSK [38]

For IIR, a new design technique called Phase Linear Regression Model (PLMR) for f-OFDM communication is proposed and analysed. The results of the new IIR outperformed FIR in the QPSK modulation with the 5th filter order are compared to a similar order of FIR. The new design is beneficial in reducing the latency and implementation cost of the filter particularly for the robust modulation like QPSK when applied in a real communication system. The proposed IIR design can also be an advantage in the future generation networks particularly for latency-sensitive applications.

1.6 Thesis Organisation

The overall structure of the thesis consists of five chapters. Chapter 2 reviews previous multiple access schemes and explains IIR and FIR concepts: link adaptation model and IIR design method. Chapter 3 presents the methodology used in this research including the research framework and PMLR technique. Chapter 4 discusses the results of the simulation, which can be divided into three categories: conventional IIR and FIR with different filter orders, link adaptation and new IIR performance. Chapter 5 concludes the research and provides recommendations for future works.

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Appendix A f-OFDM Source Code

```
s = rng(211);       % Set RNG state for repeatability

iter=1;
iter_max=30000;          % iteration
numFFT = 1024;           % Number of FFT points
numRBs = 50;             % Number of resource blocks
rbSize = 12;             % Number of subcarriers per
resource block

cpLen = 72;              % Cyclic prefix length in
samples

bitsPerSubCarrier = 2;% 2: QPSK, 4: 16QAM, 6: 64QAM, 8:
256QAM
%for indexb=12

snrdB = 10;              % SNR in dB

%snrdB = 0:5:30;
toneOffset = 2.5;        % Tone offset or excess
bandwidth (in subcarriers)
L = 6;                 % Filter length (=filterOrder+1),
odd


numDataCarriers = numRBs*rbSize;    % number of data
subcarriers in subband
halfFilt = floor(L/2);
n = -halfFilt:halfFilt;

% Sinc function prototype filter
%pb = sinc((numDataCarriers+2*toneOffset).*n./numFFT);


% Sinc truncation window
%w = (0.5*(1+cos(2*pi.*n/(L-1)))).^0.6;
%fnum = (pb.*w)/sum(pb.*w);

fnum = dsp.FIRFilter( ...
        'Numerator', [-0.00129297062251294
0.00287466681437046 ...
        -0.00198896626508255 -0.00104127087750144
0.00358851821050419 ...
        -0.00266854436758257 -0.00152676408801444
0.00474062990323758 ...
```

```
        -0.00286187361250132 -0.00277247066091464
0.00587285746088036 ...
        -0.00225186493835712 -0.00452042434014246
0.00649912631530904 ...
        -0.000784745462286556 -0.00631503894485589
0.0062695488938624 ...
        0.00130759653289175 -0.00765263676900739
0.00508900729048407 ...
        0.0035805388612653 -0.00814678837811479
0.00315088676057515 ...
        0.0055199604448021 -0.00765427535224208
0.00087542341868381 ...
        0.00670758432284593 -0.00632025849050218 -
0.00122593840765462 ...
        0.00695348418293188 -0.00452866630711557 -
0.00271451398277242 ...
        0.00635252729948489 -0.00277543386604857 -
0.00336238953331757 ...
        0.00524739512656047 -0.00150735243179677 -
0.00321975631072424 ...
        0.00411188261678024 -0.000979726331937306 -
0.00259094875175215 ...
        0.00339398574222734 -0.0011787101723204 -
0.00192883957732998 ...
        0.00337046974175737 -0.0018320456161499 -
0.00168354041335424 ...
        0.00405957905090085 -0.00250265678119563 -
0.00215519334065166 ...
        0.00521850121575128 -0.00273297490535387 -
0.00339792381731131 ...
        0.00642415433337397 -0.00219248400929695 -
0.00520420827542902 ...
        0.00720917764943498 -0.000781381874801068 -
0.00717226506854014 ...
        0.00720820672696281 0.0013412551437444 -
0.0088324621718415 ...
        0.00626763388599739 0.00381131424045872 -
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        0.0044851705690665 0.00617561217631924 -
0.00984212264602301 ...
        0.00216898254062711 0.00803081330346628 -
0.00902092500505215 ...
        -0.000267761913868458 0.00913981416262169 -
0.00757037640615827 ...
        -0.00244067713064482 0.00948842129445358 -
0.00584712575083124 ...
        -0.00411154227161785 0.00926518388339088 -
0.00419197719917961 ...
        -0.00525045359525928 0.00877257337230905 -
0.00281169474925382 ...
```

```
        -0.00602224794920579 0.00830038358399934 -
0.00171242844531442 ...
        -0.0067017181837254l 0.00800516607335774 -
0.000708788328573691 ...
        -0.00754609704856054 0.0078385495370069
0.000492194163813304 ...
        -0.00866866425475229 0.00755240087978245
0.00215837832630725 ...
        -0.00995905283069019 0.00678416660760067
0.0043953263460896 ...
        -0.0110827915167818 0.00519869067679692
0.00705353087820685 ...
        -0.0115681588545458 0.0026417321496662
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        0.0059457067579055 -0.00957368119388859
0.00138634606307455 ...
        0.00769547170098674 -0.00650349184510665 -
0.00250668270992168 ...
        0.00736134515303356 -0.00240910314618024 -
0.00499256593907904 ...
        0.00499537130371724 0.00167419901499132 -
0.00540318890029303 ...
        0.00119476544646516 0.00464668487209812 -
0.00358630421306654 ...
        -0.00302197233466137 0.00564772397743266
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        -0.00647181761629011 0.00431251939299703
0.00444817968251989 ...
        -0.00812950536312869 0.000901421195916077
0.00849632472336178 ...
        -0.00742294661311132 -0.00374504182884335
0.0110050805363855 ...
        -0.00441177004311671 -0.00842149767693316
0.0112114910700073 ...
        0.000210126117400496 -0.011886949326936
0.00896827406622053 ...
        0.00529592380861 7 -0.0132138468874027
0.0047957234176204 ...
        0.00956291799697611 -0.012053337825748 -
0.000259321699409394 ...
```

```
        0.01195379669218 -0.00873563673657472 -
0.00491891242005716 ...
        0.0119348718267122 -0.00417328560656288 -
0.00803710631769935 ...
        0.00964149297833989 0.000404799626892683 -
0.00892216823774878 ...
        0.00582703608439111 0.00380829872330514 -
0.00752136007293715 ...
        0.0016323261716538 0.00522183149393028 -
0.00441452339304242 ...
        -0.00175222946277583 0.00442161721566695 -
0.000622423981635296 ...
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        -0.00302358315745182 -0.00173608604197327
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        -0.000773096567284987 -0.00514942127817722
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        0.00260591034742895 -0.00749389614499319
0.0029139014296532 ...
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9.27479992955364e-05 ...
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        0.0105675898684877 -0.0051207138747711 -
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        0.0107392571811887 -0.00238079253390681 -
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        0.0098186970695597 0.000239575766837326 -
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        0.00836076985445592 0.00227456080616935 -
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0.0101444539223465 ...
        0.00594275138856741 0.0044625980867498 -
0.0102718036210544 ...
        0.00543219480546351 0.00527395131002566 -
0.0108680642577595 ...
        0.00516630918996285 0.00648977251407498 -
0.011954198083756 ...
        0.00471260557511973 0.00838780749430396 -
0.0132648571530267 ...
        0.00363279634618963 0.0109703808392217 -
0.01436426606516 5 ...
        0.00165551241258244 0.013973960414883 1 -
0.0148219588626788 ...
        -0.0012269839951344 4 0.016984677536413 1 -
0.0143791477550246 ...
        -0.00477252405451684 0.0196136863036951 -
0.0130439198871333 ...
```

```
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```

```
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0.0063150389448558 9 ...
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0.0045204243401424 6 ...
        -0.0022518649383571 2 0.00587285746088036 -
0.0027724706609146 4 ...
        -0.0028618736125013 2 0.00474062990323758 -
0.0015267640880144 4 ...
        -0.0026685443675825 7 0.00358851821050419 -
0.0010412708775014 4 ...
        -0.0019889662650825 5 0.0028746681437046 -
0.0012929706225129 4]);
end

filtTx = fnum;
filtRx = clone(filtTx);
%NormalizedFrequency

% QAM Symbol mapper
qamMapper = comm.RectangularQAMModulator( ...
    'ModulationOrder', 2^bitsPerSubCarrier, 'BitInput',
true, ...
    'NormalizationMethod', 'Average power');


while(iter<=iter_max)
```

```
% Generate data symbols
bitsIn = randi([0 1], bitsPerSubCarrier*numDataCarriers,
1);
symbolsIn = qamMapper(bitsIn);

% Pack data into an OFDM symbol
offset = (numFFT-numDataCarriers)/2; % for band center
symbolsInOFDM = [zeros(offset,1); symbolsIn; ...
                 zeros(numFFT-offset-numDataCarriers,1)];
ifftOut = ifft(ifftshift(symbolsInOFDM));

% Prepend cyclic prefix
txSigOFDM = [ifftOut(end-cpLen+1:end); ifftOut];

% Filter, with zero-padding to flush tail. Get the
transmit signal
txSigFOFDM = filtTx([txSigOFDM; zeros(L-1,1)]);
%filtTx([txSigOFDM; zeros(L-1,1)]);
% Plot power spectral density (PSD)
%[psd,f] = periodogram(txSigFOFDM,
rectwin(length(txSigFOFDM)), ...
%                      numFFT*2, 1, 'centered');
%plot(f,10*log10(psd));

% Compute peak-to-average-power ratio (PAPR)
PAPR = comm.CCDF('PAPROutputPort', true, 'PowerUnits',
'dBW');
[~,~,paprFOFDM] = PAPR(txSigFOFDM);
disp(['Peak-to-Average-Power-Ratio for F-OFDM = '
num2str(paprFOFDM) ' dB']);

% Compute peak-to-average-power ratio (PAPR)
PAPR2 = comm.CCDF('PAPROutputPort', true, 'PowerUnits',
'dBW');
[~,~,paprOFDM] = PAPR2(txSigOFDM);
%disp(['Peak-to-Average-Power-Ratio for OFDM = '
num2str(paprOFDM) ' dB']);

% Add WGN
rxSig = awgn(txSigFOFDM, snrdB, 'measured');
%ee=rxSig;


% Receive matched filter
rxSigFilt = filtRx(rxSig);

% Account for filter delay
rxSigFiltSync = rxSigFilt(L:end);

% Remove cyclic prefix
rxSymbol = rxSigFiltSync(cpLen+1:end);
```

```
% Perform FFT
RxSymbols = fftshift(fft(rxSymbol));

% Select data subcarriers
dataRxSymbols = RxSymbols(offset+(1:numDataCarriers));

% Plot received symbols constellation
switch bitsPerSubCarrier
    case 2  % QPSK
        refConst = qammod((0:3).', 4, 'UnitAveragePower',
true);
    case 4  % 16QAM
        refConst = qammod((0:15).',
16,'UnitAveragePower', true);
    case 6  % 64QAM
        refConst = qammod((0:63).',
64,'UnitAveragePower', true);
    case 8  % 256QAM
        refConst = qammod((0:255).',
256,'UnitAveragePower', true);
end
qamDemod =
comm.RectangularQAMDemodulator('ModulationOrder', ...
    2^bitsPerSubCarrier, 'BitOutput', true, ...
    'NormalizationMethod', 'Average power');
BER = comm.ErrorRate;

% Perform hard decision and measure errors
rxBits = qamDemod(dataRxSymbols);

ber= BER(bitsIn, rxBits);
total_run(:,iter) = ber;
qqk = ber(1);
disp(['F-OFDM Reception, BER = ' num2str(ber(1)) ' at SNR
= ' ...
    num2str(snrdB) ' dB']);
end
rng(s);
avg = mean(total_run,2);
save 10 total_run avg;
```

Appendix B Points of MSE value

F1		
SSE	HV	NSSE
5.995119	12.80693505	0.468115065
1.069044	12.80693505	0.083473874
2.550098	12.80693505	0.199118547
5.511656	12.80693505	0.430364969
7.997891	12.80693505	0.624496849
9.876266	12.80693505	0.771165463
11.27791	12.80693505	0.880609939
12.10672	12.80693505	0.945325125
12.55025	12.80693505	0.979957057
12.75173	12.80693505	0.995689443
12.80694	12.80693505	1
94.49362		7.378316329
Phase	HV	NSSE
0.4214	0.4214	1
0.2652	0.4214	0.629330802
0.121	0.4214	0.287138111
0.00563	0.4214	0.013360228
0.08501	0.4214	0.201732321
0.1588	0.4214	0.376839108
0.2237	0.4214	0.530849549
0.2869	0.4214	0.680825819
0.3306	0.4214	0.784527765
0.3246	0.4214	0.770289511
0.2332	0.4214	0.55339345

0.06687	0.4214	0.158685335
0.09827	0.4214	0.233198861
0.2069	0.4214	0.490982439
0.2681	0.4214	0.636212625
0.3233	0.4214	0.767204556
3.41948		8.114570479

F2

SSE	HV	NSSE
8.786518	12.29152	0.714844
0.878153	12.29152	0.071444
3.856593	12.29152	0.31376
6.482222	12.29152	0.527374
8.423652	12.29152	0.685322
9.915515	12.29152	0.806696
10.99384	12.29152	0.894425
11.70267	12.29152	0.952093
12.08275	12.29152	0.983015
12.24702	12.29152	0.99638
12.29152	12.29152	1
97.66046		7.945353
Phase	HV	NSSE
0.226	0.37	0.610811
0.009576	0.37	0.025881
0.1284	0.37	0.347027
0.2479	0.37	0.67
0.3112	0.37	0.841081
0.2611	0.37	0.705676
0.04785	0.37	0.129324
0.1985	0.37	0.536486
0.3154	0.37	0.852432

0.3221	0.37	0.870541
0.2738	0.37	0.74
0.1957	0.37	0.528919
0.09044	0.37	0.244432
0.04077	0.37	0.110189
0.2007	0.37	0.542432
0.37	0.37	1
3.239436		8.755232

F3

SSE	HV	NSSE
5.864587	11.49592	0.510145
0.563499	11.49592	0.049017
3.513262	11.49592	0.305609
6.713862	11.49592	0.584021
9.177256	11.49592	0.798305
10.67547	11.49592	0.928631
11.36349	11.49592	0.988481
11.49592	11.49592	1
11.41608	11.49592	0.993055
11.32018	11.49592	0.984713
11.27931	11.49592	0.981158
93.38293		8.123136
Phase	HV	NSSE
0.5357	0.5357	1
0.3002	0.5357	0.560388
0.09254	0.5357	0.172746
0.08408	0.5357	0.156954
0.1994	0.5357	0.372223
0.2505	0.5357	0.467612

0.2586	0.5357	0.482733
0.2599	0.5357	0.48516
0.2643	0.5357	0.493373
0.2449	0.5357	0.457159
0.1617	0.5357	0.301848
0.02143	0.5357	0.040004
0.1168	0.5357	0.218032
0.199	0.5357	0.371477
0.2374	0.5357	0.443158
0.2632	0.5357	0.49132
3.48965		6.514187

F4

SSE	HV	NSSE
4.58225	10.38089	0.441412
0.205808	10.38089	0.019826
2.695488	10.38089	0.259659
4.860157	10.38089	0.468183
6.502469	10.38089	0.626388
7.768447	10.38089	0.748341
8.774967	10.38089	0.8453
9.491666	10.38089	0.91434
9.99506	10.38089	0.962832
10.2828	10.38089	0.990551
10.38089	10.38089	1
75.54		7.276831
Phase	HV	NSSE
0.5904	0.5904	1
0.4997	0.5904	0.846375
0.2292	0.5904	0.388211

0.05799	0.5904	0.098222
0.104	0.5904	0.176152
0.2482	0.5904	0.420393
0.3718	0.5904	0.629743
0.4647	0.5904	0.787093
0.5068	0.5904	0.858401
0.4747	0.5904	0.804031
0.3419	0.5904	0.579099
0.1275	0.5904	0.215955
0.09383	0.5904	0.158926
0.2748	0.5904	0.465447
0.408	0.5904	0.691057
0.577	0.5904	0.977304
5.37052		9.096409

LIST OF PUBLICATIONS

Indexed Journal

1 **MUHAMMAD RAZEE, A**., Dziyauddin, R. A., Azmi, M. H., & Sadon, S. K. , "Performance Analysis of IIR and FIR Filters for 5G Wireless Networks", 2018, International Journal of Integrated Engineering.**(Indexed by SCOPUS)**

Indexed Conference Proceeding

1 **A. M. Razee,** R. A. Dziyauddin, M. H. Azmi and S. K. Sadon, "Comparative Performance Analysis of IIR and FIR Filters for 5G Networks," 2018 2nd International Conference on Telematics and Future Generation Networks (TAFGEN).**(Indexed by SCOPUS)**