Graduate School of Fundamental Science and Engineering
Waseda University

博　士　論　文
Doctoral Thesis

論　文　題　目
Studies on Four Single Sideband OFDM Modulation and Demodulation Scheme towards 5G Communication Systems

5G 通信システムに向けた 4-SSB OFDM 変復調方式に関する研究

申　請　者

Mohammed Mustafa A	ALHASANI
アルハサニ	モハッメド モスタファ ア

Department of Computer Science and Communications Engineering, Research on Ubiquitous Communication System

February, 2020

Studies on Four Single Sideband OFDM Modulation and Demodulation Scheme towards 5G Communication Systems

5G 通信システムに向けた 4-SSB OFDM 変復調方式に関する研究

February, 2020

Waseda University

Graduate School of Fundamental Science and Engineering

Department of Computer Science and Communications Engineering,
Research on Ubiquitous Communication System

Mohammed Mustafa A ALHASANI

アルハサニ　モハッメド モスタファ ア

Acknowledgements

First, Oh! Allah, all the praise is to you. I thank you all the time. I could only complete my doctoral thesis because you sustained me.

I would like to thank my supervisor, Prof. Sato, for giving me the opportunity to become a Ph.D. candidate in his laboratory. His valuable advice, guidance and support have been the cornerstone of the success of this research. His mentorship has offered helpful exposure to expert opinions as well as the opportunity to meet, discuss and share ideas with the industry experts which broaden my understanding of the research subject.

My gratitude goes to my parents, father Mustafa and mother Saleha, who had to face quite a load of hardship because of my absence. In particular, I would like to thank my family, my loving wife, Alhasani Reem, for providing me unconditional support throughout the entire process and making enormous sacrifices to get me to this stage. My children Mustafa, Abdullah and Rafa have been very patient throughout my absence and have also been giving me a strong motivation to finish my degree. Their selfless sacrifice gave me the courage to succeed. Once more, many thanks and much love to my darling wife. I would like to express my gratitude to my uncle Mohammed (Abu Musab) who passed away during my study in Japan. I wish him rest in peace at paradise. A special thanks to my uncle, Ali, for his ongoing support so that I can finish my Ph.D. study.

I would like to thank Professor Tsuda, Professor Shimamoto, and Professor Kasai for their valuable advice, suggestions, and recommendations during the entire process of this research. They have prepared me to get to this stage of my academic life. I have tremendously learned from them not only from their extensive knowledge of high-quality research but their humility and benevolence. Also, please accept my heartfelt thanks for all the support during my doctoral program to all the respectful professors, research fellows and kind workers at Waseda University.

Thank you immensely, Dr. Quang Ngoc NGUYEN, my dear Assistant Professor, a graduate of the Ph.D. program of the Graduate School of Fundamental Science and Engineering at Waseda University. I appreciate your friendship and guidance. Your efforts to guide my selection of a suitable conference and improve my academic writing skills are immeasurable. You advised and guided me on how to undertake this research on 5G technology and supported me through peer-reviews of my journal papers as well. I would also like to thank Abdeldjalil EL BEY (IMT Atlantique, École Mines-Télécom) for his useful advice on proposing the research topic and in regard to the simulation results in Chapter 2 and Chapter 3 using MATLAB. Thanks for your commitment on the weekly meetings to discuss this work.

In addition, especially I would like to express my gratitude to the Kingdom of Saudi Arabia's government, represented by the Ministry of Education for the Two Holy Mosques' Overseas Scholarship Program, for their financial support and cooperation.

Finally, I would like to say a big thank to Waseda University for giving me a great opp-ortunity to study at this famous knowledge citadel. This institution holds a special place

in my heart as both my wife and I have been benefitted as students of the University's Master and Ph.D. programs.

ALHASANI Mohammed Mustafa A

アルサセニ モハッメド モスタファ ア

Department of Computer Science and Communications Engineering,
Research on Ubiquitous Communication System

Credits and Declaration

The portion of the material in this Ph.D. dissertation has previously appeared in the following research publication:

<u>Alhasani Mohammed Mustafa A</u> Q. N. Nguyen, Ohta, G.-I, Sato, T. "A Novel Four Single Sideband M-QAM Modulation Scheme Using a Shadow Equalizer for MIMO System Toward 5G Communications". *Sensors* 2019, vol *19*, 1944

<u>Alhasani Mohammed Mustafa A</u>, Q. N. Nguyen, T. Sato and G. Ohta, "Four Single-Sideband M-QAM Modulation using Soft Input Soft Output Equalizer over OFDM" 2018 28th International Telecommunication Networks and Applications Conference (ITNAC), Sydney, NSW, pp. 1-6, 2018.

I contend, however, that this thesis includes research work that has not been previously submitted, in whole or in part, and is only my original research, except where has been declared. The research work presented in this thesis was conducted at SATO Wireless Communicating System Laboratory (Sato Lab), Department of Computer Science and Communication Engineering at Waseda University.

Abstract

Over the past few years, focus has been given to the latest 5G era of wireless technology because it appears to introduce a new and promising opportunity for low latency, high data-rate and broad bandwidth. The 5G then has been considered as a hot topic in new generation wireless technology. Typically, the 5G aims to enable high data-rate up to several gigabits per second for the realization of numerous applications such as machine to machine (M2M) applications and the internet of things (IoT).

The limitation of orthogonal frequency division multiplexing (OFDM) for fulfilling the high data-rate requirement of 5G, together with the limitation of license bandwidth, which is controlled by government regulation is one of the big challenges in the cellular communication sector. This challenge can be addressed by two approaches. The first uses the millimeter-wave (mm-Wave) in an unlicensed spectrum, and the other solution is to design a new multiplexing system such as non-orthogonal multiple access (NOMA) or orthogonal multiple access (OMA) instead of OFDM technology in the 4G system.

In this Ph.D. dissertation, first, we focused to use of high-order modulation such as M-array quadrature amplitude modulation (QAM) in 16 and 64 constellation maps for increasing the data rate and using the benefit of single sideband (SSB) in terms of spectrum allocation. The goal is to prove that OFDM technology can be applied in 5G by integrating it with four single sideband (4-SSB) M-QAM. In fact, the inter-symbol interference (ISI) degrades the performance of wireless link channels. To eliminate the effect of ISI, channel equalization is required on the receiver side. Typically, in SSB, ISI is induced by Hilbert transform which is the main function used to generate the SSB.

Therefore, designing an appropriate channel equalization is important to keep the benefit of the spectrum allocation and capacity channel of 4-SSB M-QAM. In this context, two types of equalization are proposed, provided that there are many existing equalizers. The first is called soft output soft input (SiSo) equalizer and the second is Shadow equalizer to enable efficient 4-SSB transmission scheme. It was found that the high-order QAM is impractical in widely minimum mean square error (MMSE) turbo equalizer because it degrades the wireless performance. Therefore, a special algorithm to deal with high order modulation as key function for increasing the data and enable high capacity to fulfill the 5G specification criteria is proposed. SiSo MMSE algorithm to deal with high order M-QAM modulation by add mapping and demapping function in equalizer design is also applied. In this way, the mechanism allows the system to perform high order M-QAM modulation, which realizes high data-rate by transmitting the 4-SSB M-QAM over OFDM.

Based on the observed insight, a low complexity equalizer named Shadow equalizer is proposed. Typically, different from SiSo equalizer, Shadow equalizer aims to decrease the complexities by removing the interleaver and decoder in SiSo equalizer in an iterative process. Consideration is given to improve the OFDM scheme by focusing on OFDM GI (Guard Interval) over massive MIMO. By doing so, the design of equalizer improves the OFDM performance and shows that the 4-SSB M-QAM fulfills the requirement of the 5G network.

Furthermore, since Hilbert transformer is the main cause of ISI, the performance evaluations of the two equalizer types in terms of Hilbert tap transformer are also included. The evaluation results show that the SiSo equalizer and Shadow equalizer in small tap degrades the performance due to ISI as the Hilbert transform works empirically in the small tap. The dissertation concludes with a positive outcome to expand the findings to promote the latest 4-SSB modulation and a new active research area that is expected to contribute to the future wireless network.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

4-SSB: four single-sideband

AWGN: additive white Gaussian noise

CP: cyclic prefix

GI: guard interval

IDFT: inverse discrete Fourier transform

ISI: inter-symbol interference

LMS: least mean square

LTE：long term evolution

MIMO: multiple input multiple output

MMSE: minimum mean square estimation

NOMA: non-orthogonal multiple access

OFDM: orthogonal frequency division multiplexing

OMA: orthogonal multiple access

SAC: shadow area constellation

SSB: single-sideband

SNR: single to noise ratio

ZF: zero forcing

Chapter 1

Introduction to Dissertation Organization and Problem Statement

Modern wireless communication has evolved towards the fifth-generation (5G) [1]. Since the limitation of bandwidth is controlled by government regulations, new technology modulation with high throughput is required to realize high data-rate and high capacity channels to optimize the use of spectrums. In this context, modulation technique has drawn much interest from the research community with a lot of existing emerging technologies such as orthogonal frequency division multiplexing (OFDM), nonorthogonal multiple access (NOMA).

Single sideband (SSB) is a classical topic used for transmitting data with half of bandwidth usage. Findings show that SSB is applied in optical fiber communications and also applied in radio over optical line communications [2]. Previous studies validate the SSB modulation's performance for high-speed data in gigabit per second. However, signal transmission performance using SSB in the wireless environment is degraded due to the inter-symbol interference (ISI) issue caused by Hilbert transform [3]. To this end, this research proposes a new SSB modulation scheme by combining four independent discrete signals to make a new modulation scheme, called four single sideband (4-SSB), for enabling burst mode and higher throughput with efficient spectrum usage compared to conventional SSB by using OFDM modulation.

OFDM has been adopted for many wireless technologies in licensed and unlicensed spectrums, e.g., wireless local area network (WLAN) standard IEEE 802.11a [4] and long-term evaluation (LTE) or fourth-generation (4G) in the cellular network. OFDM relied on the FDM access method for transmitting the high data rate via the division of the frequency. OFDM multiplexes the stream data over the radio with multiple independent subcarriers, which are transmitted simultaneously by orthogonality. However, the OFDM technique has not been adopted for the new 5G network since the out-band of leakage. Also, OFDM requires the synchronization for realizing high-speed of the receiver. The 4-SSB then was applied to increase the channel capacity and data rate of OFDM as one promising solution to match the requirements of 5G networks. Typically, as the wireless environment is randomly changing and data transfer using single sideband modulation is very sensitive to the random environment channel, OFDM can mitigate the ISI issue and inner channel interference. However, by using several Hilbert transforms, 4-SSB endures ISI since the delay function of Hilbert transformers, which cannot be discovered by the demodulation process in OFDM. Thus, an efficient equalizer is required in the system design to successfully recover the 4-SSB signal. In this research, two types of equalizers were applied in 4-SSB: One is the Turbo equalizer and the other is the Shadow equalizer. In this chapter, a mathematical formulation of SBB modulation is presented. Furthermore, the new modulation and demodulation of 4-SSB which can carry the double amount of information as of SSB while using only the half bandwidth of spectrum are presented.

1.1 Introduction to SSB Modulation

In general, the single sideband (SSB) [5] is extracted from the double sideband (DSB), which contains two sidebands: the upper sideband (USB) and lower sideband (LSB). Both contain the complete information of the original baseband signal. The SSB modulation only requires half of the signal bandwidth. In Figure 1.1, without loss of generality, let $x(t)$ be the baseband signal, then the mathematical model of two sidebands LSB and USB in the time domain can be expressed as:

$$x_{USB}(t) = \frac{1}{2}[x(t) + j\hat{x}(t)]; \tag{1}$$

and

$$x_{LSB}(t) = \frac{1}{2}[x(t) - j\hat{x}(t)]; \tag{2}$$

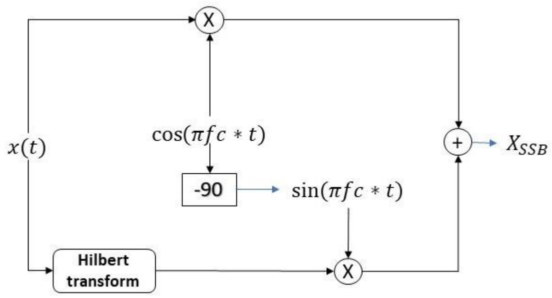


Figure 1. 1 Single-Sideband (SSB) Generated by The Hilbert Transform.

where $\hat{x}(t)$ is unknown. Then, to identify $\hat{x}(t)$, we apply Fourier Transform in both sidebands of SSB with the opposite sign as follows:

$$\begin{aligned} X_{USB}(f) = X(f)u(f) &= \frac{1}{2}X(f)[1 + sgn(f)] \\ &= \frac{1}{2}X(f) + \frac{1}{2}X(f)sgn(f). \end{aligned} \tag{3}$$

where $u(f)$ is a sign function.

We observe the Fourier transform: $j\hat{x}(t) \leftrightarrow X(f)sgn(f)$. Therefore,

$$\hat{X}(f) = -jX(f)sgn(f). \tag{4}$$

As the inverse Fourier transform for $-jsgn(f)$ in time domain is $\frac{1}{\pi t}$ in Eq (4) in time domain is equivalent to:

$$\hat{x}(t) = x(t)\ \frac{1}{\pi t}\ ; \tag{5}$$

i.e.,

$$\hat{x}(t) = \frac{1}{\pi}\int_{-\infty}^{\infty} \frac{x(\tau)}{t-\tau} d\tau \, . \tag{6}$$

The right side is Hilbert Transform [3] of $\mathrm{x}(t)$ and the signal of $\hat{x}(t)$ is the Hilbert transform of $x(t)$. We can give a more detailed expression of the Hilbert transform as the following equations:

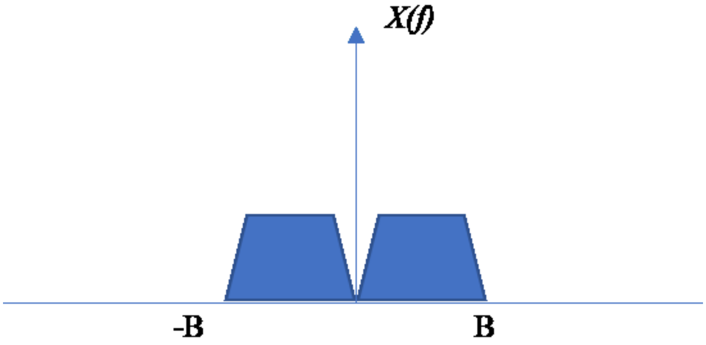
$$H(f) = -jsgn(f) \tag{7}$$

$$H(f) = -jsgn(f) = \begin{cases} -j = 1.e^{-\frac{j2\pi}{2}} \; f > 0 \\ j = 1.e^{\frac{j2\pi}{2}} \; f < 0 \end{cases} \tag{8}$$

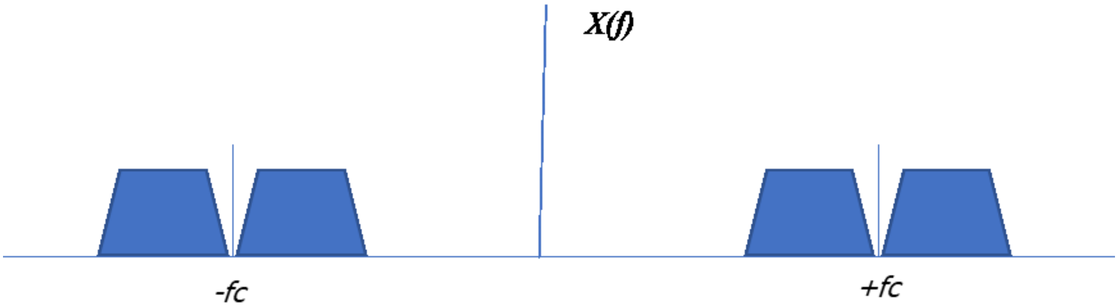
The output of signal SSB signal then can be expressed as:

$$x_{SSB}(t) = x(t)cos2\pi f_c t \mp \hat{x}(t)sin2\pi f_c t \, , \tag{9}$$

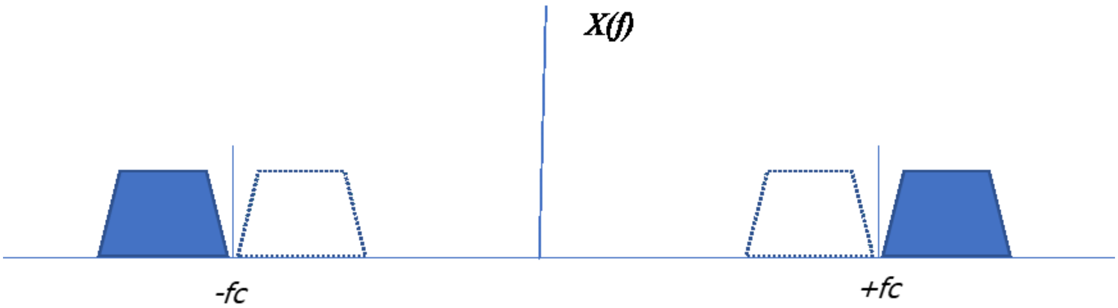
where f_c is the carrier frequency and $\mp$ denotes the sign of two sidebands: the minus sign is for USB and the positive sign is for LSB, as shown in Figure 1.2.



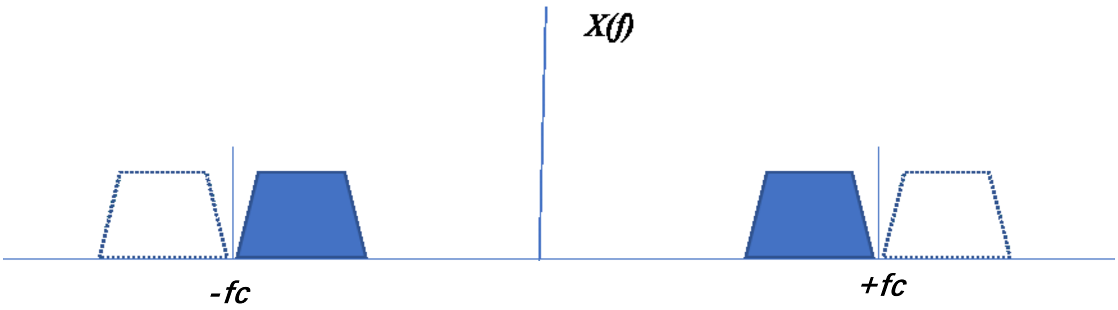
(a)



(b)



(c)



(d)

Figure 1. 2 Single-Sideband (SSB) spectrum.

1.2 Introduction to 4-SSB System

1.2.1. Four Single Sideband Modulation

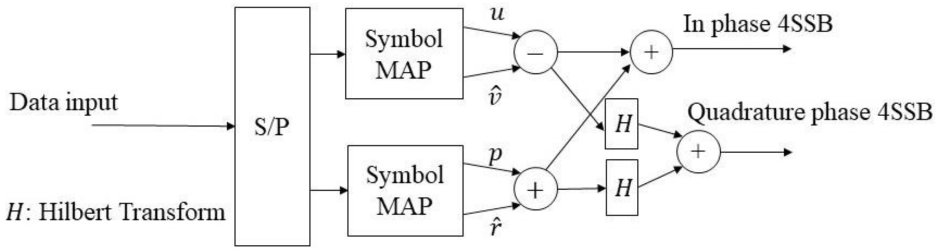


Figure 1. 3 The Four Sigle-Sideband (4-SSB) Modulation Model.

This section describes the 4-SSB modulation model using M-QAM. The proposed model uses the ideal Hilbert transform of the baseband signal $\hat{x}$. The analytical mathematical model of the upper sideband generated from baseband signal x, denoted as x_{USB}, can be expressed as:

$$x_{USB} = x - j\hat{x} \,. \tag{10}$$

Where j is a complex value equal to $\sqrt{-1}$.

Since the lower sideband is similar to the analytical value of upper sideband but with a different signed defined in the same way as of the upper sideband:

$$x_{LSB} = x + j\hat{x} \,. \tag{11}$$

These two expressions lay down the concept of SSB modulation which was used for generating 4-SSB modulation in our prior work [6].

The model configuration of 4-SSB is shown in Figure 1.3 in which the 4-SSB modulating expression can be illustrated by considering four independent real discrete sequences, denoted by *u, v, p,* and *r*. In particular, the 4-SSB signal is generated by these four signals using the following equation:

$$S_{4SSB} = S_{4SSB,I} + j.S_{4SSB,Q} \,. \tag{12}$$

Where $S_{4SSB,I}$ and $S_{4SSB,Q}$ denote the in phase 4-SSB and quadrature modulation phase 4-SSB, respectively in which:

$$S_{4\text{-}SSB,I} = u - \hat{v} + p + \hat{r} \tag{13}$$

and

$$S_{4\text{-}SSB,Q} = -\hat{u} - v + \hat{p} - r \tag{14}$$

From the previous work of 4-SSB-based modulation technique over QPSK, these equations can be applied for two BPSK signals or four complex modulated signals like QPSK and QAM. As a result, the two symbols $d_1$and d_2 of the M-QAM can be described as follows:

$$d_1 = u + j.v, \tag{15}$$
$$d_2 = p + j.r \,. \tag{16}$$

The 4-SSB signal then occupies the two-complex signal bandwidth as of d_1 or d_2 but carries twice the amount of information. This means that the 4-SSB 16-QAM has the same information as of 64- QAM or the like for the high-order modulation.

1.2.2. Four Single Sideband Demodulation

This section describes the 4-SSB M-QAM demodulation as defined in [7]. The brief process steps can be expressed as follows:

$$2.Re\left[d_{1,LSB}\right] = s_{4SSB,I} + \hat{s}_{4SSB,Q}, \tag{17}$$
$$2.Im\left[d_{1,LSB}\right] = -s_{4SSB,Q} + \hat{s}_{4SSB,I} \,, \tag{18}$$
$$2.Re\left[d_{2,USB}\right] = s_{4SSB,I} - \hat{s}_{4SSB,Q}, \tag{19}$$
$$2.Im\left[d_{2,USB}\right] = -s_{4SSB,Q} - \hat{s}_{4SSB,I} \tag{20}$$

These equations show the partial de-combination of two transmitted complex signals. The Hilbert transform tap must be equal in transmitter and receiver to ensure the quality of the transmission process. Also, it is impossible to recover two complex signals without the use of 4-SSB M-QAM demodulation.

1.3 Recent Related Work

Single sideband (SSB) is sensitive in wireless communications due to the high ISI caused by the wireless environment. Thanks to the Hilbert transform, it is feasible to generate the SSB signal from different types of modulation, e.g., QPSK, PSK, and QAM. However, for simplicity, the previous SSB-based researches are mainly applied in QPSK for increasing channel capacity. The result showed the successfully transmitted signal which compensates the ISI by using the turbo equalizer algorithm called Widely Linear minimum mean square error (MMSE) Estimation. The limitation of this approach is that the turbo equalizer is only used for QPSK then performance and feasibility are degraded in multipath fading channel because of the ISI increase [8].

A notable research investigated the increased capacity by combining four single sideband (4-SSB) QPSK [6]. This technology can double the amount of information by sending two symbols of QPSK compared to the traditional SSB QPSK. Thus, undoubtedly, it increases the number of required SSB signals using additional Hilbert transformer applied to make ISI. To solve this issue, the authors also applied the turbo equalizer to deal with QPSK modulation for enhanced efficiency.

The prior SSB-based studies are applicable in second generation (2G) and third generation (3G) wireless technology. Besides, the research of QPSK 4-SSB using the OFDM channel proves that the 4-SSB is applicable in fourth generation (4G) [7]. It also can be applied in the multipath fading channel by using the Widely Linear MMSE equalizer. The extension of this research is applying inter-canceller to improve the 4-SSB bit error rate efficiency. Currently, there is a need to apply the new idea of 4-SSB for the 5G wireless technology, but the existing researches mainly use turbo equalizers in QPSK.

Typically, the research on 4-SSB M-QAM modulation using soft input soft output (SiSo) equalizer over OFDM was proposed for increasing high data rate and capacity [9]. The researchers applied a new turbo equalizer algorithm for high order modulation. The evaluation results showed a reasonable performance in AWGN and fading channels. However, there is a need to decrease the receiver complexity without losing orthogonality for the practical applications in 5G, e.g., MIMO system [10].

To do this, the complexity was reduced by applying the shadow area constraints of QAM using multiple feedback successive interference cancellation with shadow area constraints (MF-SIC-SAC) [11]. This algorithm feeds multiple candidates for symbol estimation. However, a reduced symbol candidate’s decision is still required for realizing low energy and complexity in the equalizer.

The guard interval discrete Fourier transform spread OFDM GI DFT-s-OFDM and spectrally-preceded OFDM SP-OFDM are feasible candidates of OFDM technology to be applied in 5G [1]. The evaluation results of 4-SSB OFDM in an uncoded environment showed good performance compared to traditional OFDM thanks to the high bandwidth efficiency from the feature of SSB-based modulation. However, decreasing bit error is required for the high efficiency of bandwidth usage and efficient equalization algorithm.

Also applied, was the Turbo code with Interleaver parameters as defined by V5GTF (Verizon 5G Technical Forum) prototype for 5G radio specification [12] in 4-SSB. The proposal then investigates and proposes the system design with high bandwidth efficiency and low complexity, which implies the low energy consumption of the communication systems.

Chapter 2

Four Single-Sideband M-QAM Modulation using SiSo over OFDM

In this chapter, the single sideband (SSB) modulation through Hilbert Transform has successfully transmitted data using only half bandwidth for the same amount of contained information. Towards this line, the four single sideband (4-SSB) using QPSK modulation over OFDM was proposed as a new applicable modulation for the next generation communication system, such as 5G. This approach can improve the network efficiency; however, the inter symbol interference (ISI) is substantially introduced in 4-SSB based modulation due to the wireless channel characteristics, especially when we are increasing the order of modulation. Particularly, the Widely Linear minimum mean squared error (MMSE) equalizer is impractical in high order modulation because of its high-performance degradation. In this chapter, we propose a 4-SSB M-QAM over OFDM approach to improve the modulation feasibility and data rate, compared to the previous 4-SSB using QPSK over OFDM. The proposal uses the Infinite Length MMSE soft input soft output (SiSo) equalizer to deal with ISI induced by the finite impulse response (FIR) of the Hilbert Transform Filter. The evaluation results show that the proposed 4-SSB-based modulation technique using MMSE SiSo equalizer can considerably reduce the effect of ISI in non-ideal environments, including the additive white Gaussian noise (AWGN) and fading channel.

2.1 Introduction

To realize the sustainable next-generation communications, we need to pay attention to the quality of service (QoS) of 5G networks and beyond, especially the data rate capacity. Particularly, we are now in need of a new modulation spectrum with the minimized inter-symbol Interference (ISI) to realize an efficient transmission scheme with high data rate and capacity for the new communication system in practice [13]. To address these challenges, the presented research proposes a single sideband (SSB) modulation transformed by Hilbert Transform. The merit of this SSB signal is that it can carry the same amount of contained information while using half bandwidth as of the original signal. This improvement is clarified when applying to modulation, mainly QPSK and M-QAM [6].

However, the SSB modulation, which is inherited from amplitude modulation (AM), endures transmission performance degradation due to the wireless channel characteristics. In fact, several recent researchers have investigated the SSB modulation. For example, the research in [8] successfully transmitted the SSB signal QPSK, and the ISI is compensated by using the turbo equalization technology. Nevertheless, this approach is impractical for the high data rate transmission when we increase the order of modulation in non-ideal wireless channel environment.

To improve the capacity of SSB, in our prior work [7], we introduced an innovative method by combining four single sidebands into one, called 4-SSB. The benefit of the 4-SSB is carrying two times more information as of QPSK using the bandwidth of SSB. However, the increased number of Hilbert Transform filter induces higher ISI. To minimize the ISI effect, the authors applied equalizing algorithms, called the Widely Linear minimum mean squared error (MMSE) equalization at the receiver scheme [14]. Another extension of 4-SSB was carried over OFDM to increase the capacity of the channel. In this work, the authors use the turbo equalization algorithm to reduce the ISI effect. However, the limitation of these studies is that they only work with QPSK modulation. Thus, the modulation performance would be degraded considerably in high order modulation in practice [14]. Our presented proposal aims to enhance the capacity of 4-SSB by increasing the number of transmitted bits in high order modulation. To realize a new practical modulation in wireless channel technology, we find M-QAM beneficial for applying into 4-SSB and redesign turbo equalization algorithm for high order modulation. Towards this goal, we apply 4-SSB the approach using the soft input soft output (SiSo) [15] with infinite length MMSE equalization for the successful transmission of M-QAM 4-SSB, while keeping the benefit of 4-SSB modulation.

The remainder of this chapter is organized as follows: In Section 2.2, the proposed SiSo MMSE Equalizer in the 4-SSB M-QAM over OFDM System. Section 2.3, presents the simulation result and gives some discussion. Finally, Section 2.4 concludes the chapter with key findings and future relevant potential research directions.

2.2 The Proposed SiSo MMSE Equalizer in 4-SSB M-QAM over OFDM System

The proposed 4-SSB M-QAM over the OFDM System is a typical communication model with transmitter and receiver configuration as depicted in Figure 2.1. In transmitter, the generated random data is convoluted by the convolution coder. In addition, the interleaver minimizes the burst error. The two symbols of 4-SSB M-QAM are mapped as one symbol of OFDM. This OFDM symbol must have two times larger period duration than the symbols of 4-SSB M-QAM. The benefit of applying 4-SSB M-QAM over OFDM is to minimize ISI in the non-ideal environment for practical deployment. The detail of the proposal will be clarified in this section.

2.2.1 SiSo 4-SSB M-QAM MMSE Turbo Equalizer.

MMSE equalizer, in general, is used to minimize the mean square error as an implication to reduce the ISI in the receiver signal. The MMSE is used to compare the transmitted signal and equalized signal to minimize error.

In our MMSE SiSo system, the 4-SSB signal has suitable mapping and demapping mechanisms in equalizer for the feasible implementation in high order modulation. In principle, the turbo equalization is mainly designed to compensate the ISI by using an iterative algorithm. The system uses decoding and equalizing method to feed the prior information for coded data to provide log likelihood ratios (LLRs) [15,16]. This process begins when the channel symbol information is received after 4-SSB demodulation process and repeats through several iterative loops after the received signals d_1 and d_2 of QAM symbols form the 4-SSB demodulation. However, in the case of the Widely Linear MMSE equalizer, the performance will be degraded in the high-order modulation of QAM.

To address this issue, we applied SiSo MMSE equalizer in multilevel modulation, to overcome the ISI effect. Particularly, the turbo equalization uses the infinite MMSE and calculates the equalizer coefficient using fast Fourier transform (FFT) to enable a low complexity for the receiver process [15]. The equalization process is initiated when the two symbols of QAM are separated from 4-SSB demodulation with remaining ISI after the signal is passed through the channel noise to the OFDM receiver into the equalizer for the maximum a posterior probability information (MAP) decoder using the Bahl-Cocke-Jelinek-Raviv (BCJR) algorithm [17].

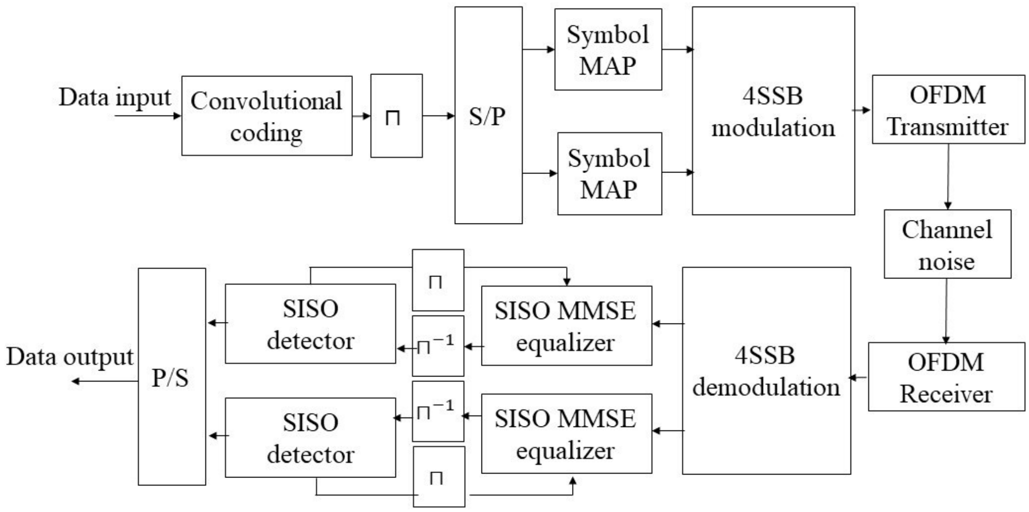


Figure 2. 1 System Configuration of 4-SSB M-QAM over OFDM

2.2.2 SiSo Mapper

In general, the QAM with Gray mapping has a set of value $\{\pm 1, \pm 3, \ldots, \pm(\sqrt{M}-1)\}$ with order $M = 2^m$. Then, we obtain the log likelihood ratio (LLR) of transmitted bits $f(c_n^1, \ldots, c_n^m)$ from the possible structure of the QAM by using $f(.)$ a function of Gray code. Let $d_{i,SSB,n}[n] = (n = 1,2,\ldots,n)$ be the transmitted signal. In the receiver, the sequence of turbo equalization can be described by the following equation [15,16]:

$$\bar{d}_n = E[d_{i,SSB,n} | \; L_\alpha^{dec}] \tag{21}$$

where L_α^{dec} denote the posterior information of LLR decoder and to SiSo decoder after the bit interleaver, we have:

$$\bar{d}_n = \sum_{P=f(c^1,\dots,c^m)\in D} d \prod_{i=1}^{m} Pr\{c_n^i = c^i | L_\alpha^{dec}\} \quad (22)$$

where the summation is carried over M-Array of complex symbol P in signal set D.

The conditional probability of SiSo, Pr, is described as:

$$Pr\{c_n^i = c^i | L_\alpha^{dec}\} = \frac{1}{2}\left(1 + (2c^i - 1)tanh\left(\frac{L_\alpha^{eq}(c_n^i)}{2}\right)\right) \quad c^i = 0,1 \quad (23)$$

and

$$L^{dec}(c_k^i) = log\frac{Pr\{c_k^i = 1 | L_\alpha^{dec}\}}{Pr\{c_k^i = 0 | L_\alpha^{dec}\}} \quad (24)$$

2.2.3 SiSo Demapper

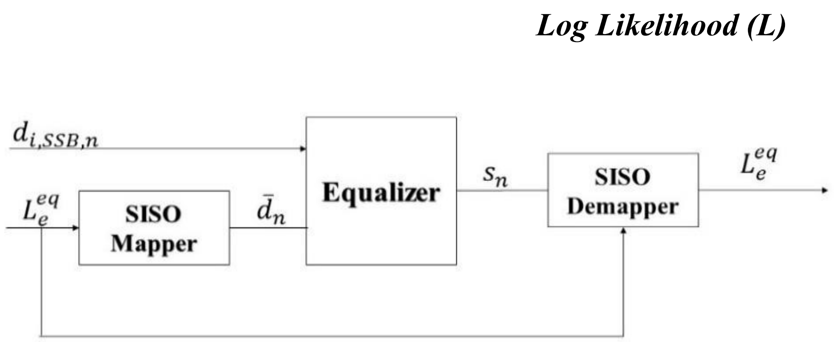


Figure 2.2 SiSo Equalizer Structure

As shown in Figure 2.2 of the SiSo Equalizer structure, the output is a posterior LLR on the coded bit, denoted as $L^{eq}(c_n^i)$. This can be computed by two inputs, s_n, and L_α^{dec}, which are the equalizer outputs and the prior LLRs sent to the SiSo decoder [15]:

$$\boldsymbol{L}^{eq}(\boldsymbol{c}_n^i) = log\frac{\sum_{d:c^i=1} \quad p\{s_n\ |d_{i,SSB,n}, L_\alpha^{dec}\}Pr\{d_n = d_{i,SSB,n}|\ L_\alpha^{dec}\}}{\sum_{d:c^i=0} \quad p\{s_n\ |d_{i,SSB,n}, L_\alpha^{dec}\}Pr\{d_n = d_{i,SSB,n}|\ L_\alpha^{dec}\}} \quad i = 1,\ldots,m \tag{25}$$

where s_n denotes the output of the equalizer and $d : c^i = j$ denotes the set symbol of $d = (c^1, \ldots, c^m) \in D$. j is a binary value which has value either 1 or 0. The variance of soft symbol σ_d^2 estimates $\bar{d}_n$. The conditional probability $p(s_n\ |d_{i,SSB,n}, L_\alpha^{dec})$ is then given by [15]:

$$p\{s_n\ |d_{i,SSB,n}, L_\alpha^{dec}\} = (\pi\sigma^2)^{-1}\, exp\left(-\frac{|s_n - g_\circ d|^2}{\sigma^2}\right) \tag{26}$$

where $g_\circ$ is the transfer coefficient filter of the equalizer and variance σ^2 is characterizing the Gaussian conditional distribution at the equalizer output. The conditional probability on the transmitted symbol is calculated from a prior binary LLR, provided by the decoder as follows:

$$Pr\{d_n = d_{i,SSB,n}\ |L_\alpha^{dec}\} = \prod_{p=1}^{m} \quad Pr\{c_n^p = c^p\ |L_\alpha^{dec}\} \tag{27}$$

The following expression shows the output of the SiSo demapper:

$$L_e^{eq}(c_n^i) = log\ log\ \frac{\sum_{d:c^i=1} \quad \left(p\left(s_n|\ d_{i,SSB,n}, L_\alpha^{dec}\right)\prod_{p=1,p\neq i}^{m} \quad Pr\{c_n^p = c^p|\ L_\alpha^{dec}\}\right)}{\sum_{d:c^i=0} \quad \left(p\left(s_n|\ d_{i,SSB,n}, L_\alpha^{dec}\right)\prod_{p=1,p\neq i}^{m} \quad Pr\{c_n^p = c^p|\ L_\alpha^{dec}\}\right)} \tag{28}$$

Now, the equalization process is used as the posterior information of the LLR decoder L_α^{dec} and derived to interleave the new updated value of prior information in equalizer L_α^{eq} Several iterations are used to obtain the inner MMSE equalizer [15].

In short, in this section, we combine the benefits of using SiSo M-QAM and 4-SSB for the efficient application of the new modulation technique to solve the existing problem of the ISI effect in the non-ideal environment.

2.3 Simulation Result and Discussion

2.3.1 4-SSB M-QAM over OFDM in Additive White Gaussian Noise (AWGN) Environment

In this section, we present the computer-based simulation of the proposed 4-SSB M-QAM system 16 and 64-QAM over OFDM system using MATLAB. The key parameters of the simulation are listed in Table 1. We use a convolutional encoder with the polynomial degree $g_0 = 3\ and\ g_1 = 7$. The output data of the encoder was interleaved using the interleaving algorithm Mersenne Twister. Before the data is modulated by 4-SSB, it was mapped using QAM Gray coding.

Figure 2.3 shows the proposed 4-SSB 16-QAM performance compared to the equivalent information amount of 64-QAM OFDM with convolution soft coded and similar scheme with 16-QAM. This simulation result demonstrated how we could carry double amount of information while decreasing the SNR by at least 2 dB. Furthermore, compared to previous work, our new design with the different equalizer obtained the same efficiency in higher-order modulation. This benefit can be applied to upcoming 4-SSB studies with high data rate speed.

Figure 2.4 shows that our system could increase modulation order to 64-QAM and still maintained high efficiency and good performance in higher-order modulation, even in the AWGN channel environment. Similarly, a comparison of the equivalent 256-QAM OFDM and 4-SSB QAM showed that our system can decrease the SNR by at least 2 dB in the same AWGN channel environment.

Parameter	Value
Encoder Rate	1/2
Interleaver Size	8000 bits
Symbol Modulation Type	QAM Gray coding
Channel Estimation	Ideal model
MMSE Equalization Sequence Length	21 symbols
The OFDM Subscriber Number	12
Hilbert Transform Filter Length	21
Channel Decoding Algorithm	Log MAP
Turbo Equalizer Sequence Length	4000 symbols
Channel Environment Model	AWGN and Rayleigh

Table 1. 1 Simulation Parameter for 4-SSB M-QAM

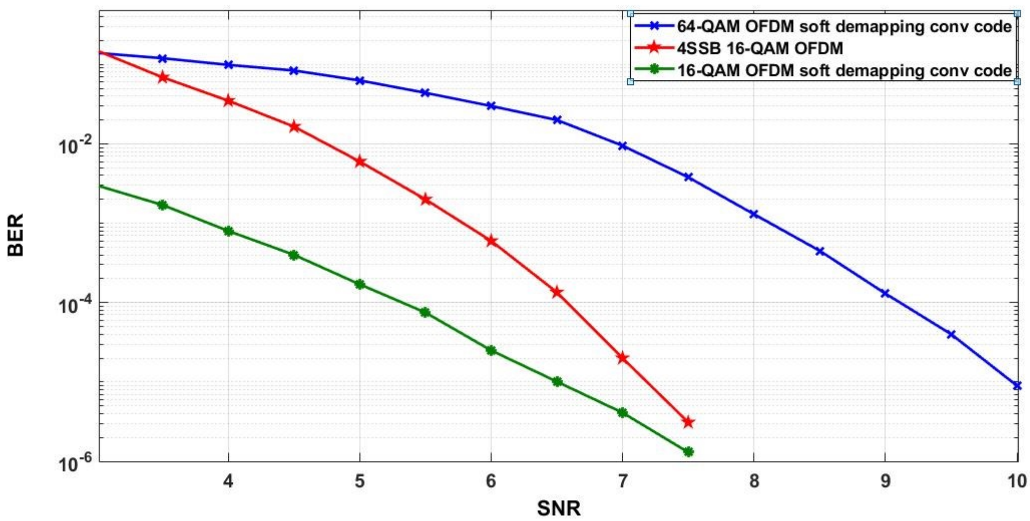


Figure 2. 3 The 4-SSB16-QAM AWGN channel

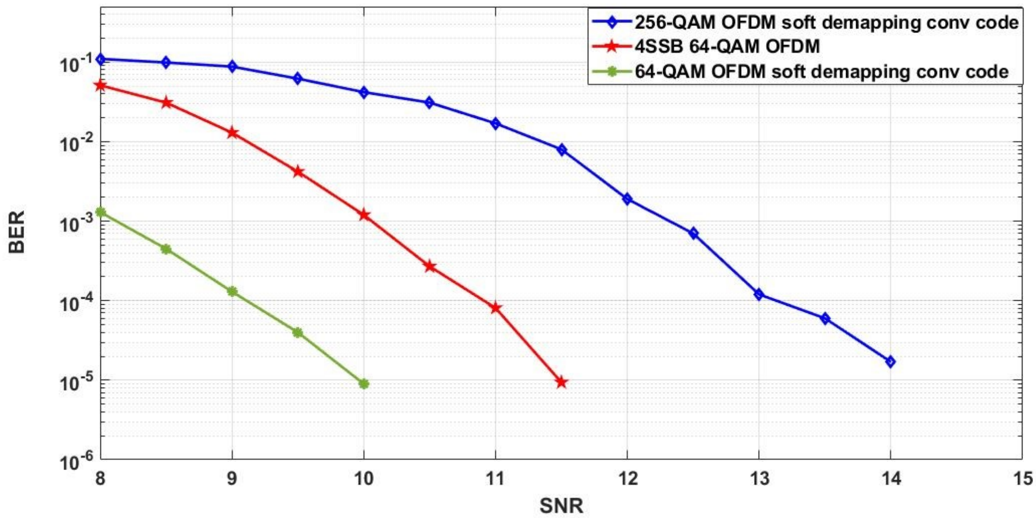


Figure 2. 4 The 4-SSB 64-QAM AWGN channel

2.3.2 4-SSB M-QAM over OFDM over Fading Channel

Figure 2.5 and Figure 2.6 evaluated the performance of our 4-SSB based proposal and other relevant soft-demapping convolution codes in which the Rayleigh Channel model was applied for the fading channel environment. In this fading channel, obviously, the high-order modulation of 64-QAM over OFDM and 16-QAM applied in 4-SSB are sensitive to the residual phase-error. This resulted in very small distances in high-order modulation. As can be observed from the small error bit performance of the proposal, we fix the arbitrary mean square error (MSE) with the Gaussian noise component *W(f)* so that the variance of noise is equal to the MSE. Thus, the channel estimation used by equalizer can be represented as the following equation [7]:

$$H_{est}(f) = H_{true}(f) + W(f) \tag{29}$$

The uniform distribution of data sources mapped by QAM Gray coding, and the large number of Hilbert transform filter tabs in 4-SSB M-QAM can be approximated as a complex Gaussian distribution. Also, the different types of QAM Gray coding of symbols were bitmapped very close to one another. However, we still obtained the sufficient spectral efficiency gain in the proposed M-QAM 4-SSB OFDM, compared to the equivalent M-QAM over OFDM.

In high bit error, it can be understood by modulated the In-phase and Quadrature of the 4-SSB in the following equation:

$$\begin{gathered} s_{4SSB,RX} = s_{4SSB,RX,I} + s_{4SSB,RX,Q} \\ s_{4SSB,RX,I} = \left(h_{Re} * s_{4SSB,I}\right) - \left(h_{Im} * s_{4SSB,Q}\right) \\ s_{4SSB,RX,Q} = \left(h_{Im} * s_{4SSB,I}\right) + \left(h_{Re} * s_{4SSB,Q}\right) \end{gathered} \tag{30}$$

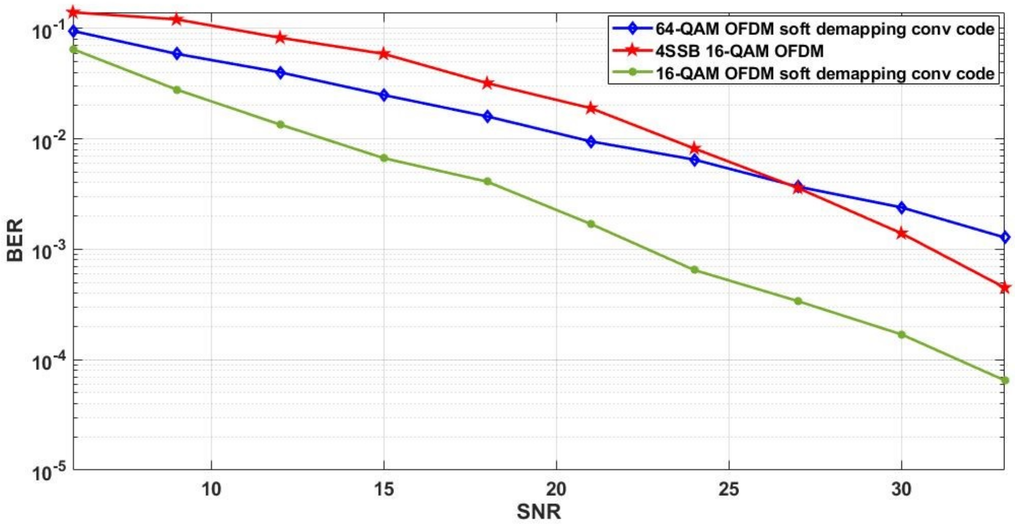


Figure 2. 5 The 4-SSB16-QAM Rayleigh channel

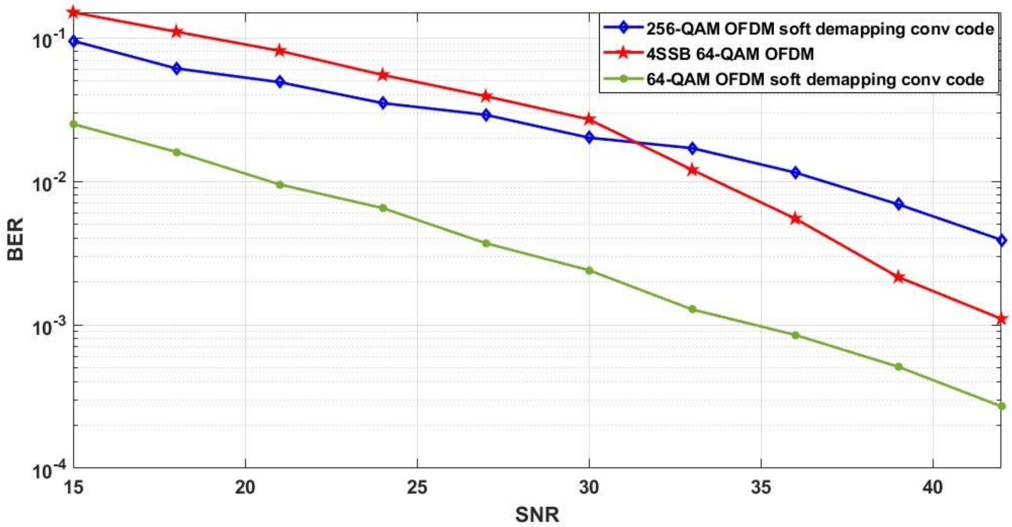


Figure 2.6 The 4-SSB 64-QAM Rayleigh channel

2.4 Conclusion

The new modulation with a high data rate is necessary for efficient communications towards 5G and beyond. To address this issue, we propose the 4-SSB M-QAM system which is successfully transmitted the signal with the minimization of ISI compared to relevant work. For practical implementations, our approach is applying the SiSo MMSE equalization algorithm in the receiver scheme so that it can minimize the ISI effect when we use high order modulation, even in AWGN and fading environments. To further improve the proposal efficiency, we will design a new equalization algorithm for the case of Hilbert Transform ISI effect as a potential approach for future work.

Chapter 3

A Novel Four Single-SideBand M-QAM Modulation Scheme using Shadow Equalizer for MIMO System toward 5G Communications

In this chapter, single sideband (SSB) modulation through the Hilbert transform has successfully transmitted data using only half bandwidth as of the traditional scheme for the same amount of contained information. Toward this end, the four single sideband (4-SSB) approach for high order modulation is a promising approach for the next generation communications by applying soft input soft output (SiSo) equalizer algorithm over OFDM. However, OFDM is challenging for realizing the feasible 5G communications, compared to the emerging techniques e.g., NOMA, OMA or MIMO. Since the 4-SSB is an orthogonal modulation that was successfully performed using the traditional OFDM. This chapter proposes a novel 4-SSB modulation scheme over OFDM GI (Guard Interval) and massive MIMO. Besides the carrier signal, from the receiver side, the shadow equalizer algorithm in an uncoded environment to achieve the 4-SSB with high efficiency from low complexity and energy consumption for 5G is also applied. The evaluation results validate that the system consumes lower energy due to low complexity gained from less number of iterations without the heavy decoding as of the 4-SSB SiSo based on turbo equalizer. In addition, the 4-SSB over the OFDM GI achieves the best performance among the relevant approaches conducted in 4-SSB. The proposal then acts as a practical communication system design to solve the ISI induced by additional Hilbert transform in the wireless environment toward 5G.

3.1 Introduction

The 5G technology is about to be launched soon to match the user demand and various requirements of future wireless communications [1]. Besides the machine type communications for ultra-reliable latency, enhancing mobile broadband is considered as the main research topic toward the next generation communication network for 5G [1]. In this framework, information-centric network (ICN) is considered a promising future internet design with the key innovative features including in-network caching and name-based forwarding to improve the network efficiency. However, by default, ICN requires caching-enabled routers that consume higher power compared to the conventual host-to-host architecture as analyzed in the previous work [18 - 20]. Also, the original forwarding strategy in ICN, leave copy everywhere (LCE), produces high cache redundancy that discourages ICN feasibility for the real-world deployment [21].

Different attempts were then made to realize the new modulation spectrum with high efficiency for next-generation communications. Particularly, orthogonal frequency division multiplexing (OFDM) is used in 4G to increase the modulation capacity and feed multi-user synchronically. For 5G, the modulation is usually conducted in non-orthogonal multiple access *(*NOMA*)* and Orthogonal Multiple Access (OMA) to realize the feasible alternative modulations [22]. Another potential research trend in 5G is to improve the OFDM scheme by adjusting its structure to fulfill the requirements of 5G such as guard interval discrete Fourier transform and spectrally preceded. OFDM, namely Gi DFT-s-OFDM and SP-OFDM respectively [10,23].

The four single sideband (4-SSB) [7] [8] is another notable work in OFDM which has the advantage of sending the double amount of same information using only half of the bandwidth compared to other OFDM modulations. The 4-SSB technology can be extended by using Hilbert transform which allows the generation of the single sideband (SSB) from different types of modulation like QPSK, PSK, and QAM. However, to the best of the knowledge, the innovative idea of the SSB technique has not been applied for 5G communications.

In this context, it has been investigated that QAM modulation can allow a communication system to improve the data rate to match 5G requirements [24]. Hence, in this research, the aim is to increase the communication bandwidth by moving toward the combined 4-SSB signals generated from two symbols of QAM. This proposal then can increase the spectrum efficiency through QAM by applying the innovative idea of 4-SSB in multi input multi output (MIMO).

The proposal complexity can be minimized by redesigning the receiver side, particularly in the equalizer. Typically, a new algorithm in the 4-SSB system, called Shadow equalizing is applied. By simulation, the new design demonstrates the low complexity by removing the process of the decoder and interleaver in iteration loops needed for the turbo equalizer. This process also refers to low energy consumption by ascending hardware components on the receiver side [11]. In the prior research [9], the 16-QAM and 64-QAM through additive white Gaussian noise (AWGN) environment and multiple path fading channels was successfully transmitted. The evaluation results show that the M-QAM 4-SSB OFDM can increase channel capacity and data rate. Thus, SSB modulation is a promising candidate to improve efficiency in 5G network. Currently, most researches have applied SSB modulation for fiber optics to enable highspeed data rates and increase capacity [2]. However, they also verify that the inter symbol interference (ISI) is a critical issue in SSB-based modulation for the wireless channel. Along this line, the proposal aims to increase the capacity of SSB by compensating ISI in uncoded system. Typically, the study investigates and proposes an enhanced mobile broadband scheme by addressing the challenging requirements in 5G through potential architectural design including the application in massive multi input multi output (m-MIMO) and new modulation spectrum for highly efficient communications with low cost and low complexity at the same time.

3.2 Related Work

The single sideband (SSB) is sensitive in wireless communication due to the high ISI caused by the wireless environment. Thanks to the Hilbert transform, it is feasible to generate the SSB signal from different types of modulation, e.g., QPSK, PSK, and QAM. However, for simplicity, the previous SSB-based researches are mainly applied in QPSK for increasing channel capacity. The result showed a successful transmitted signal which compensates the ISI by using the turbo equalizer algorithm called Widely Linear minimum mean square error (MMSE) Estimation. The limitation of this approach is that the turbo equalizer is only used for QPSK and then performance and feasibility are degraded, Because of the by ISI increase in multipath fading channel [14].

A recent research investigates the increased capacity by combining four single sideband (4-SSB) QPSK [7]. This technology can double the amount of information by sending two symbols of QPSK compared to the traditional SSB QPSK. Thus, undoubtedly, it increases the number of required SSB signals using additional Hilbert transform applied to make ISI. To solve this issue, the authors also applied the turbo equalizer to deal with QPSK modulation for enhanced efficiency.

The prior SSB-based research is applicable in 2G and 3G wireless technology. Besides, the research of QPSK 4-SSB using the OFDM channel proves that the 4-SSB is applicable in 4G [8]. It is also can be applied in the multipath fading channel by using in Widely Linear MMSE equalizer. The extension of this research is applying inter-canceller for improving 4-SSB bit error rate efficiency. Currently, there is a need to apply the new idea of 4-SSB for the 5G wireless technology but the existing researches mainly use turbo equalizers in QPSK.

Typically, the research on 4-SSB M-QAM modulation using soft-input soft-output (SiSo) equalizer over OFDM was proposed for increasing high data rate and capacity [9]. The researchers applied a new turbo equalizer algorithm for high order modulation. The result showed a reasonable performance in AWGN and fading channel. However, there is need to decrease the receiver complexity without losing orthogonality for the practical applications in 5G, e.g., MIMO system [24].

To do this, the complexity was reduced by applying the shadow area constraints of QAM using multiple feedback successive interference cancellation with shadow area constraints (MF-SIC-SAC) [11]. This algorithm feeds multiple candidates for symbol estimation. However, a reduced symbol candidate's decision is still required for realizing low energy and complexity in the equalizer.

The guard interval discrete Fourier transform spread OFDM GI DFT-s-OFDM and spectrally-preceded OFDM SP-OFDM are feasible candidates of OFDM technology to be applied in 5G. The evaluation result of 4-SSB OFDM in uncoded environment showed good performance compared to traditional OFDM thanks to the high bandwidth efficiency from the feature of SSB-based modulation. However, decreasing bit error is required for high efficiency of bandwidth usage and efficient equalizer algorithm. The proposal then investigates and proposes the system design with high bandwidth efficiency and low complexity, which implies the low energy consumption of the communication systems.

3.3 The proposed new scheme of 4-SSB with low complexity equalizer for compensating ISI

The quality of service (QoS) is a key network metric of a 5G wireless system, i.e., the successful transmission scheme which recovers the reserved signal in the receiver is important for measuring performance quality in the wireless channel environment. However, most of the current researches have focused on enabling the receiver to compensate for the effect of noise on the wireless channel. Typically, the inter-symbol interference (ISI) is produced by the channel impulse response duration less than the time symbol modulation. In this context, channel coding, MIMO technology, and channel equalization are mainly designed for improving QoS performance in wireless environments.

In this research, a new transmission scheme of 4-SSB with low equalizer complexity and the low energy consumption is proposed. Before stating the architectural design, the types of equalizer categories are briefly presented [25]: The first type of equalizer is the zero forcing (ZF) channel equalization. The main idea of forcing equalization is that the inversed channel impulse responds H^{-1} is used in the equalizer of the receiver side to equalize the original channel impulse response *H*. However, the disadvantage of this technology is increased in the implication noise, especially when the channel impulse response is very small which results in high attenuation. To minimize this effect, the MMSE equalizer is applied to improve the zero forcing equalizer performance.

The second type of equalizer is the decision feedback channel equalizer. This method of equalization includes the first equalization of zero-forcing with first symbol entry, which should be known to reduce the order of complexity. An advancement for providing high performance is to add coding channel by applying the convolution encoder and interleaving in transmission and vice versa in a receiver to minimize the error propagation in the receiving channel. This technique is called turbo equalizer, which is mainly designed to compensate the ISI by using an iterative algorithm. The system uses a decoding and equalizing scheme to feed the prior information and, in this way, the equalizer can be used for compensating ISI.

In the prior work, the turbo equalization is applied to realize the high order M-QAM in 4-SSB [9] by designing the equalizer for (SiSo) MMSE equalizer. The result showed that the M-QAM can be successfully transmitted through a variety of channels such as AWGN and multipath fading channels. The presented article is then dedicated to decreasing the complexity of the equalizer to be applied in the MIMO scheme.

The third type of equalization aims to decrease the complexity of the equalization, which can be considered as an iterative MMSE algorithm corresponding to the principle of the shadow area. This equalization is designed to make the decision of the first symbol by estimating whether the signal is strong or weak. If it is weak, the estimation will be cancelled when it is considered not close to the estimated value of the original signal to prevent the error propagation.

Then, many researches examine how to make optimal estimation with low complexity. For example, the maximum likelihood (ML) algorithm is applied for the sphere decoder (SD) [25] and lattice code. However, these two algorithms produce high complexity for high order modulation when the channel is not in good condition with a very low signal-to-noise ratio (SNR). For MIMO, the optimum maximum likelihood detection (MLD) shows a good performance by increasing the number of antennas, users and modulation levels. On the other hand, a novel vertical algorithm, called Vertical Bell labs layer space-time V-BLAST [26,27], is used in interference cancellation (IC) to achieve a better performance than the prior algorithms in which the detector made by sphere interference cancellation (SIC) is affected by error propagation.

In this article, the new scheme of M-QAM 4-SSB OFDM multiple feedback, which is used for interference cancellation with shadow area constraints (MF-SIC-SAC) is proposed. The proposal is divided into four sub-sections in the 4-SSB scheme to enable low complexity and save energy for a wide range of applicable scenarios in 5G. The research is organized as follows:

1. M-QAM 4-SSB uncodec using Shadow equalizer and its performance in terms of BER over the relevant schemes, including MIMO and OFDM GI (Guard Interval). Besides, the proposal is applied in the codec environment using Turbo coding scheme to verify the feasibility for modulation implementation toward 5G communications.
2. The proposed M-QAM 4-SSB over OFDM scheme using Shadow equalizer and its performance including complexity evaluation compared to previous work of M-QAM 4-SSB over OFDM using SiSo equalizer.
3. Comparing the proposed scheme to the related OFDM scheme in 5G.

4. Applying the proposal into massive MIMO and demonstrating the system efficiency over equivalent systems in MIMO.

3.4 The concept of application of 4-SSB into OFDM M-QAM 4-SSB uncoded system using the Shadow equalizer

In this section, the multiple feedback success interference cancellation with shadow area constraints (MF-SIC-SAC) is applied. This algorithm is utilized to address the error propagation in compensating the ISI and make feedback decisions using the SIC technique to test the SNR symbol as feedback. Then, the new scheme of M-QAM 4-SSB OFDM with MF-SIC-SAC which declines the first symbol estimation using the third aforementioned equalizer type by decreasing the number of feedback symbols is denoted. The correct constellation is still allocated in the remaining feedback symbol [11].

The selective algorithm is then optimized from the set of candidate's symbol feedbacks. This optimization algorithm is performed by selecting only one branch in the lattice tree. Consequently, this approach realizes a smart interference canceller, which is different from the hard decision of SIC or sphere decoder by searching in the optimized branch of the lattice tree to prevent from growing complexity. The Shadow area constraint is also introduced to decide whether the symbol estimation is reliable or not. The feedback output is a reliable symbol whereas the non-reliable symbol will be replaced by the concentrated symbol producing by SAC.

3.4.1. System Model

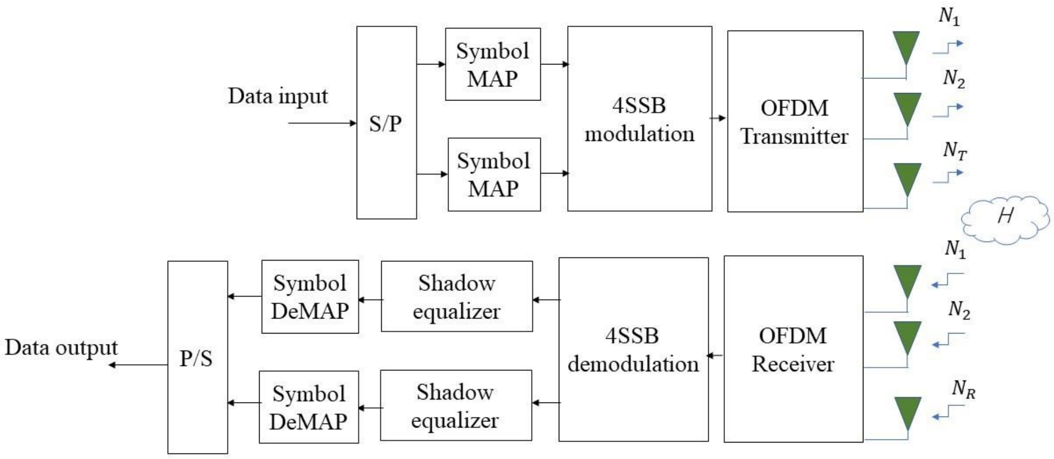


Figure 3. 1 The proposed 4-SSB Multi-Input Multi-Output (MIMO) System.

The proposed system model is depicted in Figure 3.1. The system has two major devices in a typical communication system: transmitter and receiver. Suppose that the traditional MIMO system has N_T transmitter antennas and N_R receiver antennas, and the number of receiver antennas generates more than that of transmitter antennas, i.e., $N_R > N_T$. Firstly, the transmission scheme is fed by the independent data binary value $\{1,0\}$ with equal probability. Each binary in the uncoded system then will be mapped using two parallel QAM Gray codec symbols. For M-QAM signals, the complex value is represented in the real and imaginary part of the symbol which takes value in the general set of two M-QAM proceeded by 4-SSB modulation $\{\pm 1, \pm 3, \dots, \pm(\sqrt{M} - 1)\}$ to produce one profile called 4-SSB M-QAM with the same bandwidth has of two symbols of QAM.

To realize a feasible approach in MIMO, the system transmitter is translated into $N_T \times 1$ vector $x_{4-SSB,n}[i] = \left[x_{4-SSB,1} x_{4-SSB,2} \dots x_{4-SSB,N_T}\right]^T$. This sequence of symbols is transmitted over a flat fading channel. The 4-SSB M-QAM is first demodulated by the OFDM modulation then follows a 4-SSB demodulation process and sampled in the receiver with N_R antennas. The received signal after demodulation process is collected in $N_R \times 1$ $r[i] = [r_1[i], r_2[i], \dots, r_{N_r}[i]]^T$ and can be expressed as:

$$r[i] = Hx_{4-SSB,n}[i] + v[i] \tag{31}$$

After the signal is sampled, the signal can be represented in the discrete-time equivalent channel, which is affected by additive, zero-mean, circularly symmetric white Gaussian noise $v[i]$ with total variance σ_v^2. The receiver signal mathematical model is:

$$r_n = \sum_{l=0}^{L} h_l x_{4-SSB,n-1} + v_n \tag{32}$$

Where the set $\{h_l\}$ denotes the $L+1$ coefficient of the discrete-time equivalent model. In MIMO, the element $h_{nR,nT}$ of the $N_R \times N_T$ channel matrix H denotes a complex channel gained from the n_T^{th} transmitted antenna and n_R^{th} with receiver antenna. For simplicity, it is considered that the H complexity corresponds to the optimized ordering. The arrangement is denoted as norm function $\|H_1\|, \|H_2\|, \dots, \|H_{N_T}\|$ where (H_n) represents the n^{th} column of H.

3.4.2. The proposed 4-SSB M-QAM MF-SIC-SAC Scheme Design

The proposed system consists of three algorithmic categories. First, the conventional SIC scheme is introduced. Then, the branch of MF-SIC is explained. The MF structure requires additional computational complexity. However, the Shadow concentration is designed to decrease the complexity of the system. The process is made by the design of a reliable and non-reliable symbol [11].

In general, the conventional SIC algorithm is used in the MMSE filter as $N_R \times 1$ filter vectors corresponding to all the antennas. The function of MMSE is to estimate the symbol by making the candidate symbol as null or successful cancellation for perfect optimized detection. The stream of the antenna is denotes as $\hat{d}_{i,SSB,n}[i] = \left[\hat{d}_{i,SSB,1}\hat{d}_{i,SSB,2} \dots \hat{d}_{i,SSB,N_T}\right]^T$ where the receiver $\hat{d}$ is an estimated symbol of 4-SSB.

The SIC algorithm of the estimated symbol is expressed as follows:

$$\hat{d}_{i,SSB,n}[i] = Q(w_n^H \, \check{d}_{i,SSB,n}[i]) \tag{33}$$

Where the $Q(.)$ function denotes the hard slice function of the receiver symbol which is summarized in the following conditional equation:

$$\begin{gathered} \check{d}_{i,SSB,n}[i] = d_{i,SSB,n}[i], n = 1, \\ \check{d}_{i,SSB,n}[i] = d_{i,SSB,n}[i] - \sum_{k=1}^{n-1} (H)_k \check{d}_k[i], \qquad n \leq 2, \\ w_n = (\bar{H}_n \bar{H}_n^H + \sigma^2 I)^{-1} (H)_n \end{gathered} \tag{34}$$

Where $\bar{H}_n$ denotes the represented matrix with columns $n, n+1, \dots, N_T$. $\check{d}_n$ is the receiving symbol of the 4-SSB post-demodulation process. This symbol is obtained after the constellation of the previously detected $(n-1)$ symbols.

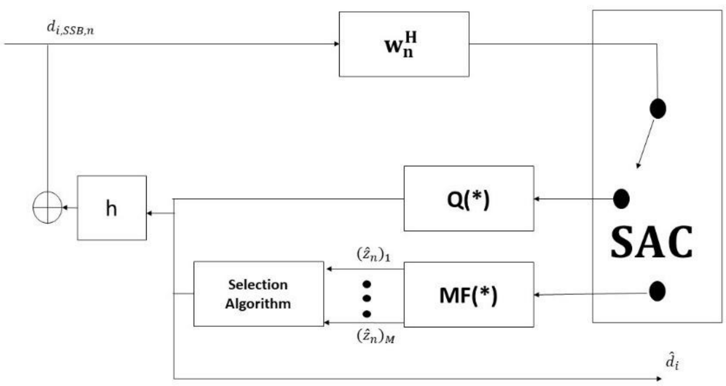


Figure 3. 2 The Shadow equalizer in the 4-SSB MIMO System.

3.4.3. The MF-SIC in 4-SSB scheme

The proposal of MF-SIC is 4-SSB as shown in Figure 3.2. The two symbols enter the MMSE to decrease error estimation so that the candidates of symbol detection can be reflected. Without the loss of generality, the process through the pseudocode algorithm of MF-SIC-SAC [11] as in Algorithm 1 is presented. The system starts by detecting each data stream $\hat{d}_1, \hat{d}_{2,}, \ldots, \hat{d}_{N_T}$ which can be obtained in each stage. The constellation is located within the shadow. The algorithm of soft decision $\tilde{d}_n[i] = w_n^H d[i]$ applied to check the decision of symbol is reliable or non-reliable as follows [11]:

1) Reliable Decision: if the algorithm of SAD considers that the symbol $\tilde{d}_n[i]$ is reliable, the function of hard slice decision is used for both data stream for hard decision as well as the cancellation function for the next symbol. The conventional in SIC algorithm will match hard slice decision as follows:

$$\hat{d}_n[i] = Q(\tilde{d}_n[i]) \tag{35}$$

2) The symbol is decided as non-reliable: if the previous exhaustive decision is non-reliable. Then, several candidate's vectors are generated, and the aforementioned conventional SIC will decide the candidate's symbol as minimal as possible for saving energy saving. Algorithm 1 selects which candidate symbol is the nearest one to the original symbol.

Particularly, the selection algorithm is used to choose the best candidate symbol in 4-SSB. The procedure has two steps. First, multiple feedback (MF) is generated. As shown in Figure 3.2, the MF algorithm is applied after SAC makes the non-reliable decision. To optimize the symbol candidate in the first iteration, the nearest M constellation points by the soft decision of MMSE filter $\tilde{d}_n[i]$ is selected. This filter is defined as the function of multiple feedbacks as the following expression:

$$L = MF(\tilde{d}_n[i]) \tag{36}$$

The constellation of the M-QAM symbol candidates can be represented by the subset of $L = [\, c_1, c_2, \ldots, c_M] \subseteq A$. The nearest M constellation refers to the signal to noise ratio (SNR) as a higher value of SNR implies a smaller value of M.

In Algorithm 1, a new factor called $\hat{z}_n[i]$ which is represented by *M x 1* vectors is also introduced. The output of MF generates the nearest constellation of symbol candidate represented by:

$$\hat{z}_n[i] = [\, c_1, c_2, \ldots, c_M]^T \tag{37}$$

Algorithm 1. The Algorithm of MF-SIC-SAC in 4-SSB domain.

Initialization of MMSE filter:

$w_n = (\bar{H}_n \bar{H}_n^H + \sigma^2 I)^{-1} (H)_n, n = 1, \ldots, N_T$

  for $n = 1$ to N_T **do**

    $\tilde{d}_n = w_n^H d_n$

    If $\tilde{d}_n \in$ Shadow Area

      $\hat{z}_n = [\, c_1, c_2, \ldots, c_M]^T$

      for $m = 1$ to M **do**

        for $j = n$ to N_T **do**

          $\hat{d}_{j,m} = \check{d}_n - (H)_n (\hat{z}_n)_m$

            $- \sum_{p=n+1}^{j-1} (H)_p b_{p,m}$

          $b_{j,m} = Q(w_j^H \hat{d}_{j,m})$

        end for

      end for

      $b_m = [b_{1,m}, \ldots, b_{N_T,m}]^T$

      $m_{opt} = arg \min_{1 \le m \le M} \| d_{i,SSB,n} - H b_m \|^2$

      $\hat{d}_n = (\hat{z}_n)_{m_{opt}}$

    else

      $\hat{d}_n = Q(\tilde{d}_n)$

    end if

    $\check{d}_{i,SSB,n} = d_{i,SSB,n} - \sum_{k=1}^{n-1} (H)_k \hat{d}_k$

  end for

This stage is significant in making the decision feedback optimal. The previous step of MF-SIC is to prevent the system from making error propagation.

The second step is for the candidate symbol. In this step, the objective is to select optimal candidates from the symbol $\hat{z}_n[i]$. Let b_m denote a new vector symbol of the optimal candidates with a range of $1 \leq m \leq M$.

As each b_m represents m^th candidate in each n to N_T stage of processing, the candidate vector symbol is expressed by the following transform matrix:

$$b_m[i] = \left[\hat{d}_n[i], \ldots, \hat{d}_{n-1}[i], b_{n,m}[i], \ldots, b_{j,m}[i], \ldots, b_{N_T,m}[i]\right]^T. \quad (38)$$

This vector value is filtered by the MMSE filter described as follows:

$$b_{j,m}[i] = Q(w_j^H \hat{d}_{j,m}[i]) \quad (39)$$

where $\hat{d}_{j,m}$ denotes the canceled receiver feedback vector in the m^th stage. The reason for applying the MMSE vector is to decrease the complexity of the system.

$$b_m = \left[b_{1,m}, \ldots, b_{N_T,m}\right]^T \quad (40)$$

The algorithm then selects the optimal feedback corresponding to the following constraint:

$$m_{opt} = arg\, min_{1\leq m\leq M} \|d_{i,SSB,n} - Hb_m[i]\|^2, \quad (41)$$

$$\hat{d}_n = (\hat{z}_n)_{m_{opt}} \quad (42)$$

.

3.4.4. The constraint of the Shadow of M-QAM

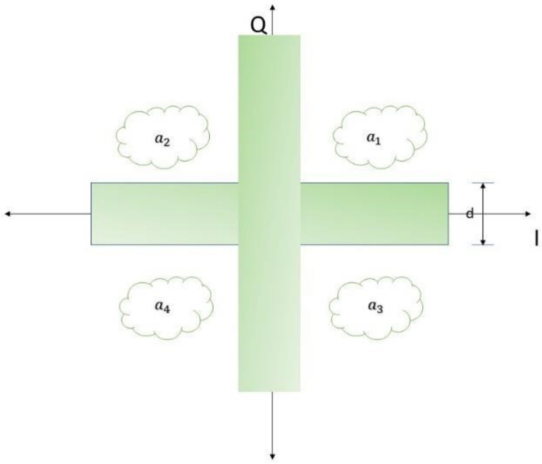


Figure 3. 3 4-QAM Shadow Area Constellation.

Figure 3.3 represents the shadow constraint in 4-QAM. The shadow area has distance *d* with the original MF algorithm. However, the main difference between the development of decision feedback and the SAC is the feedback representation. Specifically, when the feedback is zero, the error propagation will be increased. SAC avoids null feedback by applying the shadow distance to determine the probability of soft decision as the following equation:

$$\hat{d}_n[i] = (\hat{z}_n[i])_{m_{opt}} \quad (43)$$

The system avoids the null feedback by generating MF to minimize the error burst.

In general, QAM constellation can be determined since $\tilde{d}_n$ refers to reliability rated from shadow distance *d* [11].

$$\begin{cases} \left[R[\tilde{d}_n] - R[a_{K,n}]\right] > \frac{d}{2}, \\ \left[I[\tilde{d}_n] - I[a_{K,n}]\right] > \frac{d}{2}, \end{cases} \quad (44)$$

.

The high SNR means low complexity as it is aimed to get the best case for estimating symbols. The remaining part of the equation is $[a_{K,n}]$ which is the constellation point of M-QAM with the nearest soft decision of $\tilde{d}_n = w_n^H d_n[i]$ in the n^{th} layer:

$$a_{K,n} = \arg\min_{a_{k \in A}} \|w_n^H \check{d}_n[i] - a_k\|^2, k = 1, \ldots, C \quad (45)$$

3.5 Performance Evaluations and Discussion

3.5.1 M-QAM 4-SSB uncoded system using Shadow equalizer evaluation and complexity analysis

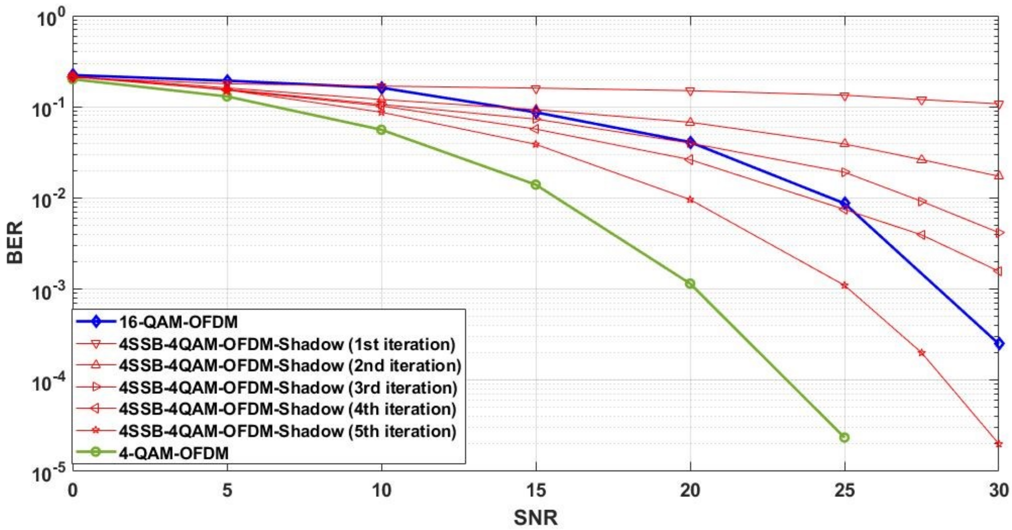


Figure 3. 4 4-QAM 4-SSB Shadow equalization iteration evaluation compared to the relevant modulation schemes.

Complexity analysis: the equalization problem can be seen as an iterative MMSE algorithm based on the shadow area principle. As N is the frame length, the first iteration includes the computation of matrix inversion with the complexity of the order N^3. For the other iterations, the complexity order is about $(N - n_i)^2$ where n_i is the number of symbols considered as reliability over the iteration i. Therefore, the total complexity is about $O(N^3)$ dominated by the complexity of the first iteration.

Performance evaluation: Figure 3.4 shows the 4-QAM 4-SSB shadow equalization iteration performance compared to the equivalent scheme in uncoded system. Overall, the 4-QAM 4-SSB OFDM performance can reach SNR efficiency close to equivalent amount information as of 16-QAM after the fifth iteration, as verified in the prior work in 4-SSB [9]. However, the 4-QAM OFDM performs worse than 4-QAM 4-SSB because OFDM scheme carries less amount of bit compared to 4-SSB.

Specifically, the iteration process in 4-QAM 4-SSB Shadow initially estimated by $\check{d}_n$ since no previous symbol is available with the steady tendency of SNR. In the second iteration, the first estimation is fed as the previous symbol and the *(n-1)th* iteration is slightly improved compared to the first iteration. In the third iteration, the symbol has good SNR for an estimation which is equivalent to 16-QAM OFDM performance by 20 dB SNR. Similarly, the fourth iteration is equivalent to the bit error rate of 16-QAM till 25 dB SNR. In the last iteration, the 4-QAM 4-SSB has the peak efficiency of bit error rate as it can achieve bit error to10^{-3} at 25 dB SNR but the equivalent scheme of 16-QAM OFDM still performs better with the same SNR. The red line demonstrates the performance of the constellation of 4- QAM modulation over OFDM.

Besides, to verify the efficiency of the proposal for practical deployment, the Turbo code as a classical coding approach for the transport channel is taken. Specifically, in Figure 3.5, the BER performance of different modulation schemes in the coded case using Turbo code with comparable information data-rates is compared. This shows that the coded 16-QAM with code rate R=1/2 outperforms the other modulation schemes; however, it also represents the lowest spectrum efficiency with only two information bits per channel use. In contrast, the 4-SSB 16-QAM (R=1/2) and 64-QAM (R=2/3) modulation schemes represent the same bit rate with four information bits per channel use, and the evaluation result demonstrates that after SNR=25 dB, the 4-SSB 16-QAM outperforms the 64-QAM by achieving a gain of 3 dB at BER=10^{-3}.

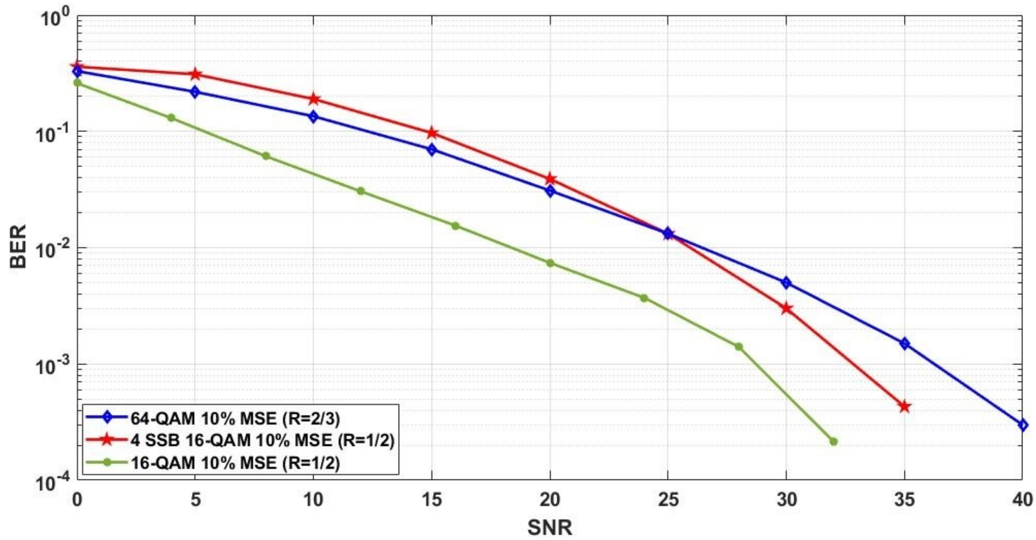


Figure 3. 5 4-QAM 4-SSB with the Turbo code system using Shadow equalization compared to the relevant modulation schemes.

3.5.2 M-QAM 4-SSB uncoded system using Shadow equalizer evaluation and complexity in massive MIMO

The MIMO system is key to modern wireless technology toward 5G. The main goal of MIMO application is to realize the diversity and spatial multiplexing. Diversity enables the system to achieve robust communications through transmission with an independent channel. On the other hand, spatial multiplexing can save energy consumption by increasing the data rate and efficiently use bandwidth.

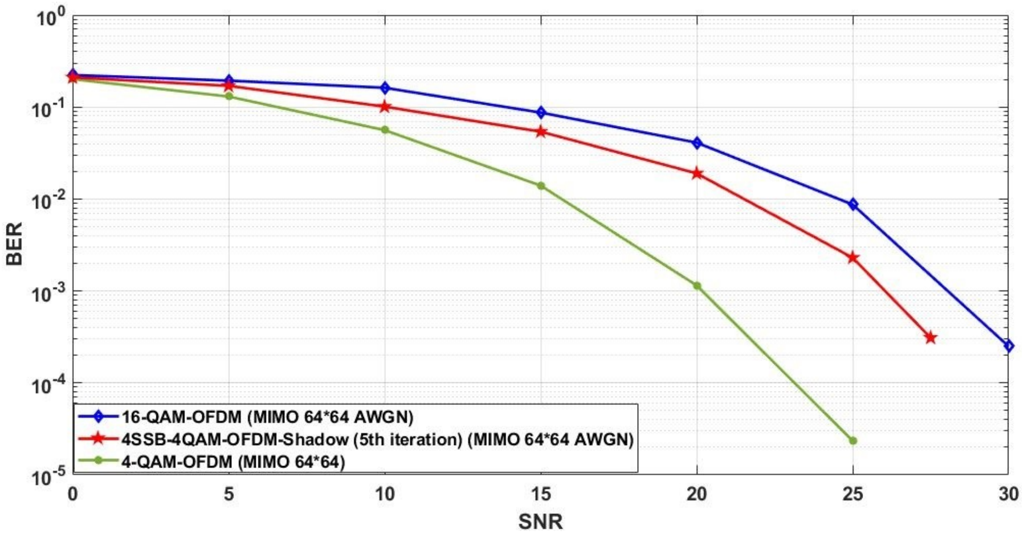


Figure 3. 6 4-QAM 4-SSB Shadow in massive MIMO compared to relevant schemes in the Additive White Gaussian Noise (AWGN) environment.

In the proposal, the 4-SSB M-QAM performs slightly close to the performance of 16 QAM over the OFDM scheme. However, the 4-SSB M-QAM with shadow equalizer decreases the SNR compared to the previous scenario as y both the equalization and massive MIMO is applied. This efficiency is clearly demonstrated after 20 dB SNR. On the other hand, the 4-QAM OFDM has good performance because it carries only two bits (Figure3.6).

Figure 3.7 shows the performance evaluations of the 4-SSB-based proposal and other relevant MIMO schemes in which the Rayleigh channel model is applied for the multipath fading channel environment. In this channel, the Quadrature Modulations of 4-QAM and 16-QAM over OFDM applied in 4-SSB are sensitive to the residual phase error, resulting in distances in quadrature-order modulation.

The uniform distribution of data sources mapped by QAM Gray coding and the large number of Hilbert transform filter tabs in 4-SSB M-QAM can be approximated as a complex Gaussian distribution. Additionally, the different types of QAM Gray coding of symbols are bitmapped very close to one another. However, sufficient spectral efficiency can still be obtained.

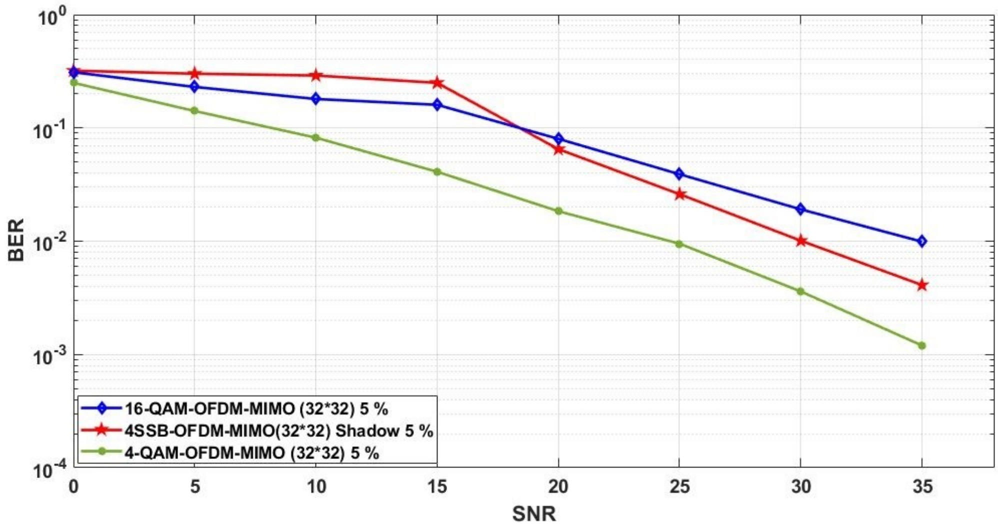


Figure 3. 7 4-QAM 4-SSB Shadow in massive MIMO compared to the relevant modulation schemes in Rayleigh Channel environment.

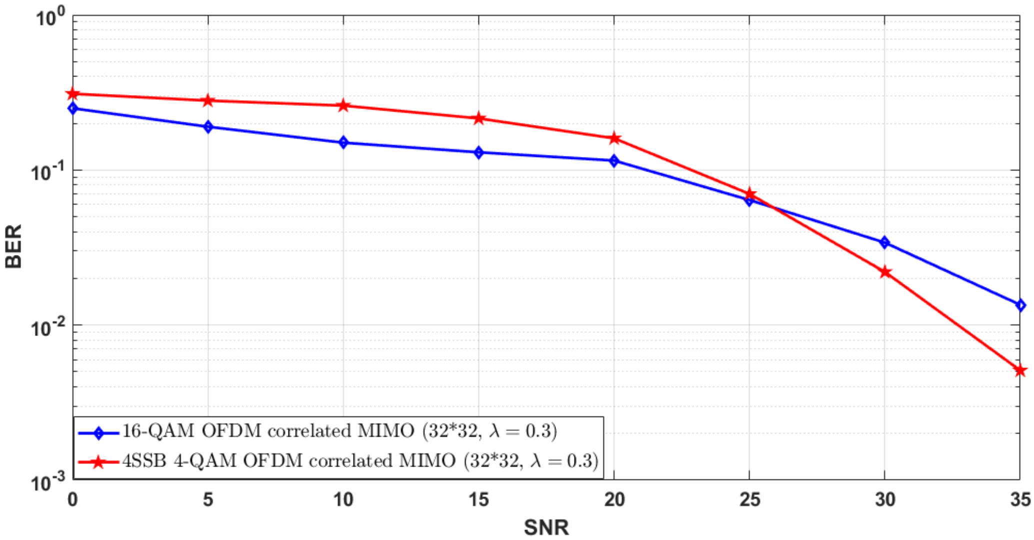


Figure 3. 8 4-QAM 4-SSB Shadow in correlated MIMO compared to the relevant modulation schemes in the uncoded system under Rayleigh Channel environment.

Next, a more realistic MIMO scenario by showing the impact of the channel correlation is considered. Particularly, a spatially correlated MIMO fading model using the Kronecker product model is adopted [27]. This model assumes the fading statistics of the transmit and receive antennas are independent. The correlation matrices are then computed based on the Bessel distribution correlation and the distance between antennas. In Figure 3.8, the distances between antennas as d = 0.3 λ is taken. As the effect of the channel correlation is examined for the uncoded case, it is shown that the same results can be obtained in the case of non-correlated Rayleigh channel.

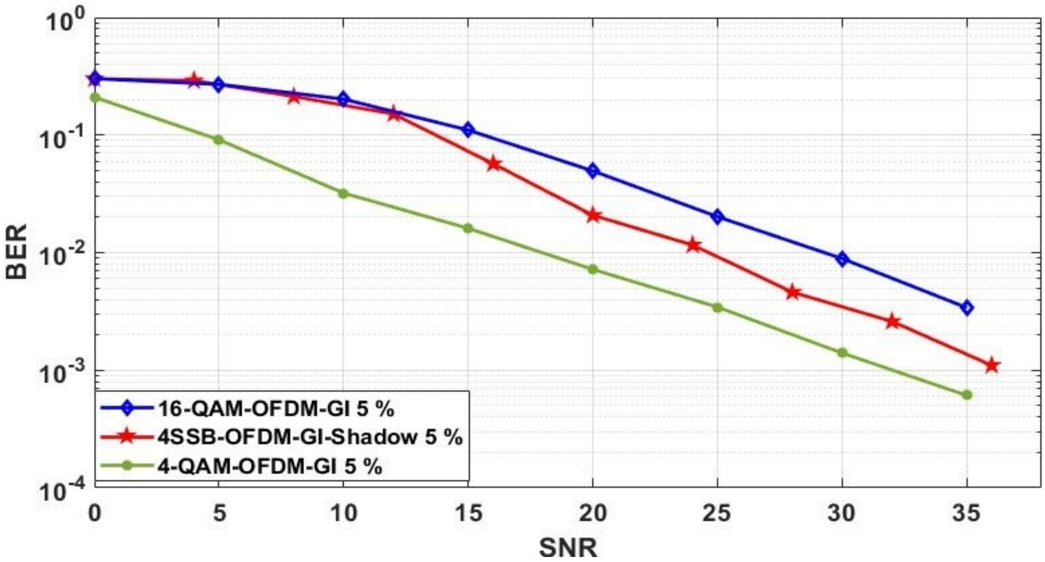


Figure 3. 9 4-QAM 4-SSB Shadow applied in Orthogonal Frequency Division Multiplexing Guard Interval (OFDM-GI) compared to the relevant modulation schemes in the Rayleigh Channel environment.

Finally, 4-SSB using Shadow equalizer in OFDM-GI as a new modulation to match the 5G requirements is applied. Specifically, the discrete Fourier transform spread OFDM GI (DFT-s-OFDM-GI) replaces cyclic prefix (CP) instead of the Guard Interval. In addition, the OFDM-GI can choose the time duration in a flexible way. Typically, this improves the performance of 4-SSB by using additional Hilbert transform for symbol generation. Hence, the Hilbert transform induces delay by 90 degrees, i.e., ISI is increased as well. Figure 3.9 shows an interesting result by investigating the evaluation history of 4-SSB. First, 4 bits in 4-QAM 4-SSB performs close to 2 bits of 4-QAM after 35 dB SNR. The remaining evaluations show that the proposal can reach Shannon boundary in the codec system since it performs well under the harsh condition of the uncoded environment.

3.6 Conclusion and Future Work

In this article, a new modulation that enables high data rate with low complexity for efficient communications toward 5G and beyond is proposed. To make the proposal feasible for the 5G communication network, both the receiver and carrier signals to improve the overall system performance are taken into consideration.

First, the signal is transmitted through uncodec system to minimize the effect of ISI in AWGN and fading multipath channel. The approach of 4-SSB using Shadow equalizer can efficiently decrease the complexity of the receiver by removing the iterative turbo equalization and decoding process required in a traditional 4-SSB SiSo equalizer. In addition, the proposal is applied using turbo coded transport channels with the interleaver parameters as suggested by the V5GTF's 5G specification regarding multiplexing and channel coding to verify the efficiency and enable the feasibility of the proposal at the same time.

Next, the 4-SSB in massive MIMO to serve the huge demand of the user and enable data rate in the 5G network is applied. The evaluation results demonstrated that the proposed system performs well in the case of 64 x 64 MIMO and 32 x 32 MIMO under the AWGN and Rayleigh channels. The correlation Rayleigh to realize a realistic scenario in the ideal case toward 5G communications is also applied. Besides, the lowest value of SNR in OFDM-GI is achieved.

To enable a complete modulation scheme in various environments toward 5G, handling the Doppler effect and mobility will be the focus points in future work. Also, besides Turbo code, there is the plan to conduct the proposed 4-SSB modulation scheme with other promising source coding techniques for 5G implementation, including Polar code with successive cancelation list and linear BLOCK error correction code, and low-density parity-check code (LDPC) with sum-product and linear error correction code.

Chapter 4

The Hilbert transform performance in 5G using Four Single Sideband with SiSo and Shadow Equalizers

4.1 Introduction

The new wireless technology requires data transmission with a high data-rate and the quality of service to match the large content demand. In this context, the single sideband (SSB) technology [5] has demonstrated unique merit with the capability to transmit the information through transmitter using only half of the spectrum bandwidth, i.e., save the power compared to the equivalent schemes. However, the SSB is an Amplitude modulation which is affected by the sensitivity of the random nature of the wireless channel environment. Hence, SSB endures the symbol inter-symbol interference (ISI), especially in high data-rate and high-order modulation like quadrature amplitude modulation (QAM) and phase shift keying (PSK).

In SSB, the signal is generated using the Hilbert transform [3]. Currently, most of the research dealt with the non-ideal Hilbert transform in infinite impulse response (IIR) whereas the finite impulse response (FIR) is studied for the practical system implementation. The SSB is validated for optical communication to reach a high data rate in gigabit per second. Recently, the most common SSB technology is twin SSB to double the amount of information on both sides of the spectrum, instead of only one side as of the conventional SSB. Twin SSB, however, is mainly applied for wired networks using the optical modulator in which the coefficient of channel fading is equal to one.

Also, given that the spectrum bandwidth is limited and bounded by the government regulations, we need a new kind of modulation to match the 5G specification. Currently, there are several existing modulation technologies that realize the high data rate to guarantee the quality of service, e.g., the non-orthogonal multiple access (NOMA) and the orthogonal multiple access (OMA). The main concept of these technologies is provided the many users with the same allocation frequency which implying the save the power spectrum.

To exploit the advantage of SSB, several researches started improving the capacity of the SSB scheme by combining it with quadrature phase-shift keying (QPSK) to increase the capacity of the channel due to the fact that SSB requires the orthogonal basis. For instance, the authors in [5] applied widely minimum mean square error (MMSE) algorithm in turbo equalizer to compensate ISI. The result showed good performance by successfully transmit data over QPSK with SSB. However, the research has a limitation, which is difficult to be applied in 4G and beyond systems because the data rate does not match the requirements of modern wireless systems.

To improve the SSB capability, Ohta et al. [6] proposed the new modulation scheme by combining the four independent signals to produce the four single sideband (4-SSB).

This modulation can carry a double amount of information while using half of the bandwidth compared to the conventional modulation of SSB. Specifically, 4-SSB enables the same feature as of Twin SSB and is applicable to the wireless communication systems in which Twin SSB does not work because the channel fading is randomly changed in the dynamic wireless environment, which is presented by Gaussian distribution. To decrease the ISI effect, the widely MMSE turbo equalizer is applied to keep the quality of the received signal [14].

The 4-SSB technique is also improved by applying the OFDM for increasing the capacity which matches the requirement in 4G [7]. However, on this day, 5G has been launched and it enables ten times higher data-rate compared to 4G. For that reason, the 4-SSB over OFDM scheme was improved by applying new turbo equalizers called Shadow equalizer and SiSo equalizer to increase the data rate for the high-order modulation like 16-QAM and 64-QAM [9].

Since the Hilbert transform with finite impulse response (FIR) has not been considered in previous 4-SSB studies, in this research, we study the effect of Hilbert transformer in 4-SSB toward 5G and beyond to improve the receiver signal performance with decreased complexity.

4.2 The Hilbert Transform Approach

In general, the Hilbert transform is mainly used for signal processing applications like Fourie, Z and Laplace, Hartley, and Wavelet transform [28-32]. In this research, the modulation and demodulation procedure of the 4-SSB scheme for the Hilbert transform is conducted in the same way as Chapter 2 in which SSB is generated mainly through using the Hilbert transform. Also, to be applied in the time domain, the Hilbert transform only changes the frequency sign rather than changing the signal domain. This characteristic of the Hilbert transform will be described in the next section.

4.3 Hilbert Transform with The Mathematical Model

Together with the Fourier transform, Hilbert transform realizes a well-known transform for the analytical spectral signal. The mathematical model of the Hilbert transform is performed by using the feature of the Fourier transform.

To enable various applications, we use the Hilbert transform for the 4-SSB modulation and demodulation process to enhance the received signal performance and compensate ISI at the same time by using the different type of equalization process.

In particular, the mathematical model for the Hilbert transform can be described by considering a Fourier transform signal pair as follows:

$$u(t) \overset{\mathrm{F}}{\Leftrightarrow} U(f) \tag{46}$$

where $u(t)$ is a unit step function $U(f)$ can be represented in the frequency domain as a complex number with a real part and imaginary part as:

$$U(f) = A(f) + jB(f) \tag{47}$$

$U(f)$ is then an analytical signal of complex Fourier signal of $u(t)$. By using the kernel of integral information for signal $u(t)$, the Hilbert transform can be defined in the time domain as follows:

$$v(t) = H[u(t)] = \frac{1}{\pi t} * u(t) \tag{48}$$

$$u(t) = H[u(t)]^{-1} = -\frac{1}{\pi t} * v(t) \tag{49}$$

$u(t)$ and $v(t)$ realize the pair of Hilbert transform and can be denoted as the following transformation:

$$u(t) \overset{\mathrm{H}}{\Leftrightarrow} v(t) \tag{50}$$

In the next section, the Hilbert transform with infinite impulse response FIR is described.

4.4 Hilbert Transform with Finite Impulse Response (FIR)

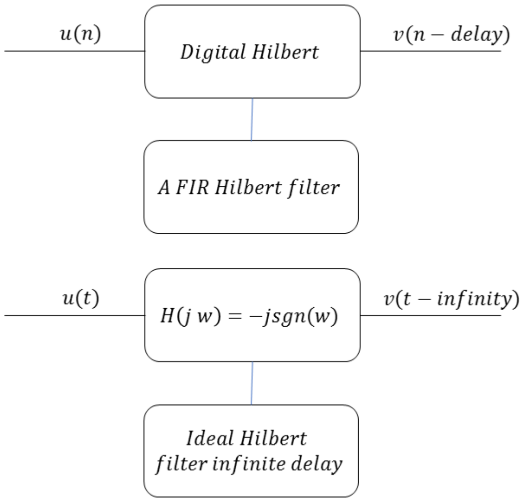


Figure 4. 1The structure of two types of Hilbert transform (infinite and finite impulse response)

Since modern communications include the built-in digital signal processors, all of the signals must be converted to a digital signal before they are initially processed. This process is known as an analog to digital converter (A/D). The Hilbert transform is mainly performed in the digital domain called the discrete Hilbert transform or Finite impulse response FIR. Figure 4.1 illustrates two types of Hilbert transform: one includes the infinite delay in the continuous-time domain, whereas the other is finite or discrete-time domain (FIR). The 4-SSB system is designed to use Hilbert transform as FIR to realize a practical wireless system. By default, the filter of Hilbert transform includes 21 taps in transmission and receiver, as suggested by our prior study [8]. In this research, to deduce the highly feasible and efficient system, we evaluate the optimized number of taps to gain high performance with low complexity using different types of equalization like SiSo with turbo equalizer and Shadow equalizer.

4.5 Hilbert Transform Tap with a Mathematical Model in 4-SSB

As can be seen in Figure 4.1, the ideal Hilbert transform is $(jw) = -jsgn(w)$ where $sgn(w)$ is the sign function of the frequency domain. Then, if the frequency is in a positive band, the sign will become negative and vice versa Figure 4.2. The impulse response in each tap of Hilbert transform in the time domain can be represented as the following equation:

$$h = \frac{1}{\pi t} \tag{51}$$

The cascade tap results in higher delay, but there is a trade-off between the optimized number of tap and efficient performance of 4-SSB in a wireless channel environment.

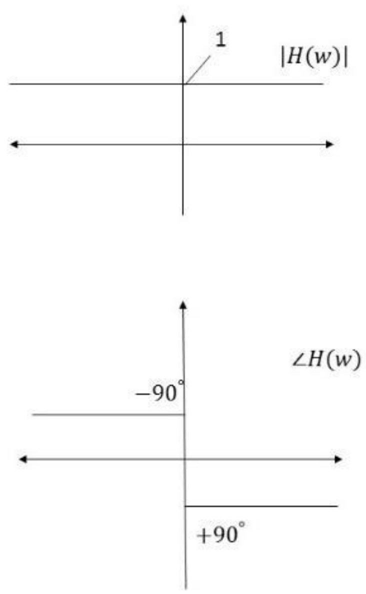


Figure 4. 2 Hilbert transform impulse in infinite

4.6 Hilbert Transform Model with Odd and Even Number of Taps

The impulse response in odd and even number of taps in discrete Hilbert transform, can be represented by the notation g . The discrete signal x can be represented with discrete Hilbert transform as the following equation:

$$\hat{x}[n] = \sum_{k=\frac{-N}{2}+1}^{\frac{N}{2}} g_{HT}[k]\, x[n-k] \tag{52}$$

Let *N* denoted the number of taps in Hilbert filter transform, the Hilbert impulse response with respect to the tap number N can be expressed as:

$$N\ even:\ g_{HT}\,[k] = \begin{cases} \frac{2}{N}\sin^2\left(\frac{\pi.k}{2}\right)\cot\left(\frac{\pi.k}{N}\right) & ,k \neq 0 \\ 0 & ,k = 0 \end{cases} \tag{53}$$

$$N\ odd:\ g_{HT}\,[k] = \begin{cases} \frac{2}{\pi.k} & ,k\ odd \\ 0 & ,k\ even \end{cases} \tag{54}$$

Note that due to the Hilbert transform properties in the discrete domain, the performance of the proposal remains unchanged in 4-SSB modulation and demodulation processes, irrespective of the number of taps (odd or even). The USB and LSB in 4-SSB are then represented in all discrete domain as the following expressions:

$$x_{SSB}[n] = \sum_{k} h_{SSB}[k]x[n-k], \tag{55}$$

$$h_{SSB}[k] = \begin{cases} \pm j.\, g_{HT}\,[k], & k \neq 0 \\ 1 \pm j.\, g_{HT}\,[k], & k = 0 \end{cases} \tag{56}$$

Equation (55) is a discrete convolution with channel impulse response of Hilbert transform. As the Hilbert transform in the continues time domain was mentioned in previous sections, Equations (54) and (55) form the mathematical model of Hilbert transform, which is applicable in the 4-SSB model for the performance evaluation section (Section 4.7).

4.7 Performance Evaluations and Discussion

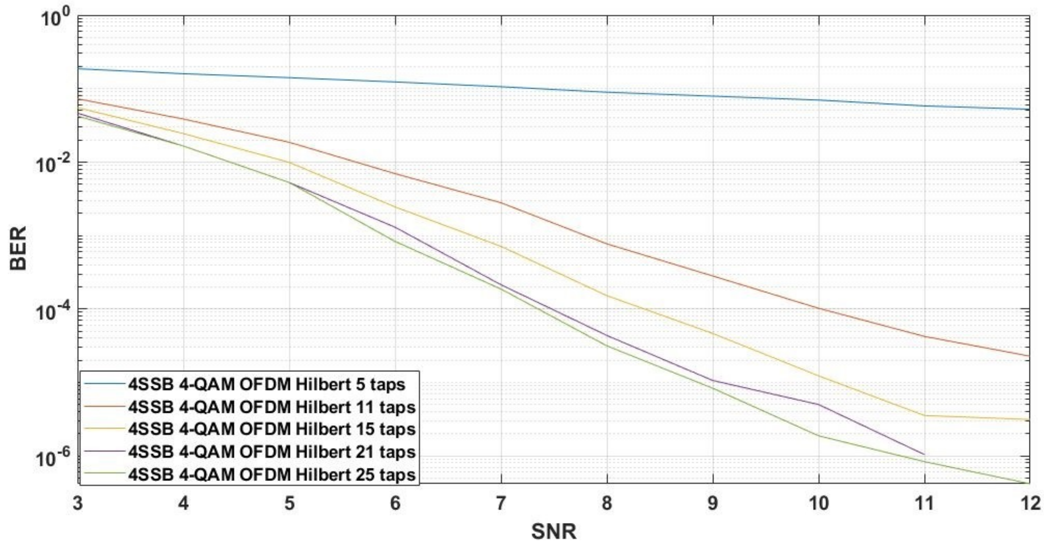


Figure 4. 3 The Hilbert transform tap evaluation in SiSo equalizer

4.7.1 The Hilbert transform performance using Turbo equalizer with SiSo in AWGN

In this section, the effect of the number of Hilbert transform taps in odd is described. It can be deduced from equation (54) that half of the coefficient of the impulse response is equal to zero (i.e., k is even and differs from zero). Figure 4.3 shows that the Hilbert transform does not work well because to realize the benefits of Hilbert transform, a high number of taps is needed to make an appropriate approximation. However, when the number of taps is increased to 11, the performance of 4-SSB is increased as the SNR reaches 12 dB. When the number of taps is increased to 21, the proposal achieves the best performance under the Additive white gaussian noise AWGN.

4.7.2 The Hilbert transform performance using Shadow equalizer in AWGN

Figure 4.4 shows the performance of the Hilbert transform tap evaluation via the simulation of Shadow equalizer in AWGN when the SNR range is taken from 0 dB to 30 dB. As can be seen, the Hilbert transform with the Shadow stills perform well even with the smallest number of taps. Although SISO equalizer shows a higher BER performance when the number of taps is not greater than 11, we can observe that Shadow equalizer achieves a higher and more stable performance for the 4-SSB received signal when the number of taps is greater than 15, provided that Shadow equalizer is run under the uncoded system compared to the SISO coded system.

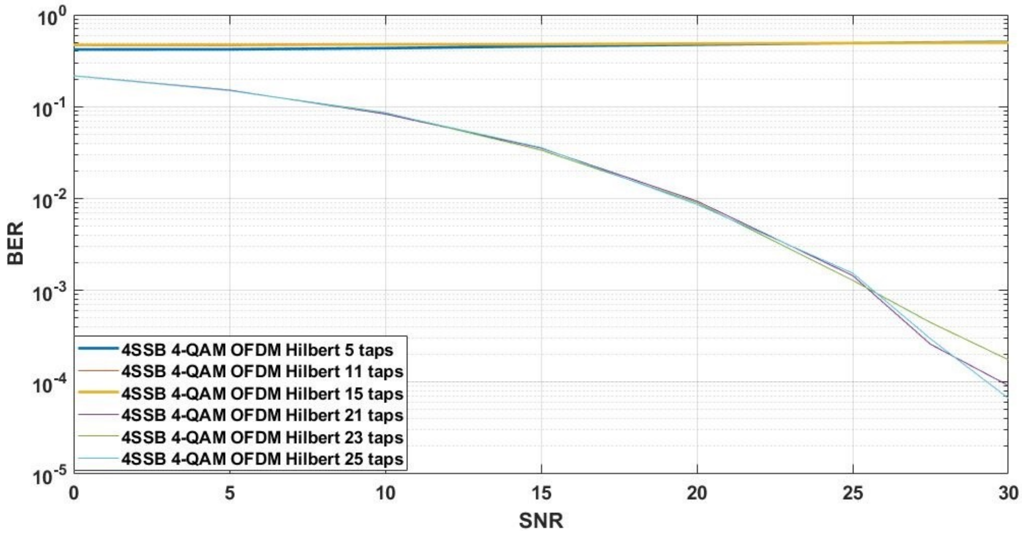


Figure 4. 4 The Hilbert transform tap evaluation in Shadow equalizer

4.8 Conclusion and Future Work

In this chapter, the Hilbert transformer tap effects in the 4-SSB model system are studied. Two types of equalizer including SiSo and Shadow equalizers were evaluated. A new design of Hilbert transforms in 4-SSB based wireless communications and its performance evaluations of the effect as one step to verify the proposed scheme for the 5G network is proposed. However, some necessary work remains regarding using OFDM technology like synchronization in the up and downlink channels. Also, for future work we will make or modifying the structure of filter to make robustness of effect in the small number of Hilbert transform.

Chapter 5

Conclusion, Closing Remark, and Future work

5.1 Summary and Concluding Remarks

This dissertation had analyzed, designed and implemented a novel four single-sideband modulation scheme with different types of equalizer in wireless communications for 5G and 6G era. To the best of my knowledge, although there are many researchs works on my research topic, this is the first work that explicitly addresses the receiver design with high data rate and low complexity in an SSB-based scheme. Particularly, most of the existing work in SSB focuses on optical communications for increasing the data rate or channel performance in the wired optical channel. On the other hand, this dissertation also aims to address critical challenges in 5 G SSB modulation towards future deployable and feasible communication by increasing the data rate and capacity of the wireless channel.

To the goal of improving the efficiency of 4-SSB through high order modulation M-array QAM to enhance the data rate, this dissertation proposed the M-QAM 4-SSB modulation to enable more bits in the signal symbol with features of 4-SSB in terms of bandwidth efficiency by minimizing the ISI induced by the Hilbert transform.

Especially, this research designs and implies the different channel equalization in the 4-SSB receiver side by successfully implementing the SiSo equalizer and shadow equalizer as an adaptive equalizer mechanism to compensate ISI. Moreover, this dissertation utilizes the cutting-edge MIMO technology to further improve the 4-SSB scheme with improved data rate and robustness for the ISI effect by proposing GI-OFDM mechanism. Hence, the proposed M-QAM based 4-SSB outperforms 16 QAM, and 64 QAM with high data rate and high throughput in terms of bit per second and supports the high content demand from users in 5G network with the improved QoS and wireless performance.

To address the problems of the ISI and the dramatically random change of wireless channel due to the multipath fading, this research purposes the SiSo MMSE equalization algorithm, which deals with M-array QAM. Thanks to SiSo equalizer, the system can map and de-map the QAM symbols so that the best symbol estimation can be selected through the iterative process. The proposed SiSo equalizer in the M-QAM scheme can increase both the data rate and channel capacity in the overall context transmitted bit error rate over the total SNR compared to the relevant systems.

By integrating the MIMO and Shadow equalizer into the proposal, this research can decrease the complexity of the receiver by removing the decoding and iterative process in turbo equalizer. The evaluation results demonstrate that Shadow equalizer and MIMO in 4-SSB offer the high output data rate with optimized receiver complexity compared to the M-QAM 4-SSB in SiSo turbo equalizer.

In conclusion, this research proposes the M-QAM 4-SSB with the redesigned channel equalization algorithm for possible dedicated communication real-time applications and services. The results of the dissertation show that the proposal allows a suitable 4-SSB, which can be implemented with M-QAM over both OFDM and MIMO, for potential and feasible adoption of 5G in real wireless channel scenario. Thus, I believe that the proposed M-QAM 4-SSB can become a feasible approach to modulation technology with a future that can be deployed high data rate with the increased capacity toward the future wireless communication system beyond 5G.

5.2 Future Work

The dissertation is a thorough research study focusing on a new modulation to allow high data rates for 5 G wireless design. In reality, this work is not complete, and in the later phase there are several improvements to be made. In order to extend the plan for realistic 5 G deployment to real-life implementations, I plan to research ongoing related research work. I intend to analyze and investigate several constellation models for a high data rate in order to improve the efficiency of the 5 G modulation for future studies.

Next, I want to propose a new 4-SSB over OFDM by considering the signal synchronization by designing a promising sampling and quantization mechanism. Also, I will consider the frequency offset effect in the Hilbert transform to realize a new aggregation scheme, which will enhance the 4-SSB performance and can be validated by fabrication in FPGA by using the HDL platform.

Finally, I plan to standardize the 4-SSB modulation for future wireless communication networks.

Bibliography

[1] X. Zhang, J. Wang, "Statistical QoS-driven power adaptation for distributed caching based mobile offloading over 5G wireless networks", 2017 IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS), pp. 760-765, 2017.

[2] J. Shi, Y. Zhou, Y. Xu, J. Zhang, J. Yu and N. Chi, "200-Gbps DFT-S OFDM Using DD-MZM-Based Twin-SSB With a MIMO-Volterra Equalizer," in IEEE Photonics Technology Letters, vol. 29, no. 14, pp. 1183-1186, 2017.

[3] Stefan L. Hahn, Hilbert Transforms in Signal Processing, Artech House, 1996.

[4] M. K. A. Aziz, M. R. G. Butler, A. Doufexi, A. R. Nix and P. N. Fletcher, "Indoor throughput and range improvements using standard compliant AP antenna diversity in IEEE 802.11a and ETSI HIPERLAN/2," IEEE 54th Vehicular Technology Conference. VTC Fall 2001. Proceedings (Cat. No.01CH37211), Atlantic City, NJ, USA, pp. 2294-2298, 2001.

[5] L. Zhang et al., "Beyond 100-Gb/s Transmission Over 80-km SMF Using Direct Detection SSB-DMT at C-Band," in Journal of Lightwave Technology, vol. 34, no. 2, pp. 723-729,2016.

[6] G. Ohta, M. Nanri, M. Uesugi, T. Sato, H. Tominaga, “A Study of New Modulation Method Consisted of Orthogonal Four SSB Elements Having a Common Carrier Frequency,” IEEE, The 11th International Symposium on Wireless Personal Multimedia Communications (WPMC) Lapland Finland, 2008

[7] Y. Jiang, Z. Zhou, M. Nanri, G. I. Ohta and T. Sato, "Performance Evaluation of Four Orthogonal Single Sideband Elements Modulation Scheme in Multi-Carrier Transmission Systems," 2011 IEEE Vehicular Technology Conference (VTC Fall), San Francisco, CA, pp. 1-6,2011.

[8] B. Pitakdumrongkija, H. Suzuki, S. Suyama and K. Fukawa, "Single sideband QPSK with turbo equalization for mobile communications," 2005 IEEE 61st Vehicular Technology Conference, Stockholm, pp. 538-542, 2005.

[9] Mustafa, A.M.; Nguyen, Q.N.; Sato, T.; Ohta, G. Four Single-Sideband M-QAM Modulation using Soft Input Soft Output Equalizer over OFDM. In Proceedings of the 2018 28th International Telecommunication Networks and Applications Conference (ITNAC), Sydney, Australia, pp. 1–6, 2018.

[10] Cai, Y.; Qin, Z.; Cui, F.; Li, G.Y.; McCann, J.A. Modulation and Multiple Access for 5G Networks. IEEE Commun. Surv. Tutor. vol 20, pp. 629–646, 2018.

[11] Li, P.; de Lamare, R.C.; Fa, R. Multiple feedback successive interference cancellation with shadow area constraints for MIMO systems. In Proceedings of the Seventh International Symposium on Wireless Communication Systems, Heslington, UK; pp. 96–101, 2010.

[12] Verizon 5G TF; Air Interface Working Group. Verizon 5th Generation Radio Access; Multiplexing and Channel Coding (Release 1); Verizon Wireless: New York, NY, USA, 2016.

[13] X. Zhang and J. Wang, "Statistical QoS-driven power adaptation for distributed caching based mobile offloading over 5G wireless networks," 2017 IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS), Atlanta, GA, pp. 760-765, 2017.

[14] M. Tuchler and A. C. Singer, "Turbo Equalization: An Overview," IEEE Transactions on Information Theory, vol. 57, no. 2, pp. 920-952, 2011.

[15] C. Laot, R. Le Bidan and D. Leroux, "Low-complexity MMSE turbo equalization: a possible solution for EDGE," in IEEE Transactions on Wireless Communications, vol. 4, no. 3, pp. 965-974, 2005.

[16] D. Kim, H. Kim and G. Im, "Soft Log Likelihood Ratio Replacement for Low Complexity Maximum-Likelihood Detection," in IEEE Communications Letters, vol. 16, no. 3, pp. 296-299, 2012.

[17] J. Gunther, D. Keller and T. Moon, "A Generalized BCJR Algorithm and Its Use in Iterative Blind Channel Identification," in IEEE Signal Processing Letters, vol. 14, no. 10, pp. 661-664, 2007.

[18] Q. N. Nguyen; Arifuzzaman, M.; Miyamoto, T.; Takuro, S. An Optimal Information Centric Networking Model for the Future Green Network. In Proceedings of the 2015 IEEE Twelfth International Symposium on Autonomous Decentralized Systems, Taichung, Taiwan, pp. 272–277, 2015.

[19] Q. N. Nguyen, Arifuzzaman, M.; Sato, T. Proactive-caching based information centric networking architecture for reliable green communication in intelligent transport system. In ITU Kaleidoscope: Trust in Information Society; IEEE: Barcelona, Spain, pp. 1–7, 2015.

[20] Q. N. Nguyen, M. Arifuzzaman, K. Yu and T. Sato, "A Context-Aware Green Information-Centric Networking Model for Future Wireless Communications," in IEEE Access, vol. 6, pp. 22804-22816, 2018.

[21] Q. N. Nguyen ; Liu, J.; Pan, Z.; Benkacem, I.; Tsuda, T.; Taleb, T.; Shimamoto, S.; Sato, T. PPCS: A Progressive Popularity-Aware Caching Scheme for Edge-Based Cache Redundancy Avoidance in Information-Centric Networks. Sensors, vol 19, pp. 694 ,2019.

[22] D. Zhang, Y. Liu, Z. Ding, Z. Zhou, A. Nallanathan and T. Sato, "Performance Analysis of Non-Regenerative Massive-MIMO-NOMA Relay Systems for 5G," in IEEE Transactions on Communications, vol. 65, no. 11, pp. 4777-4790, 2017.

[23] U. Kumar, C. Ibars, A. Bhorkar and H. Jung, "A Waveform for 5G: Guard Interval DFT-s-OFDM," 2015 IEEE Globecom Workshops (GC Wkshps), San Diego, CA, pp. 1-6, 2015.

[24] Z. Chen et al., "A 256-QAM 39 GHz Dual-Channel Transceiver Chipset with LTCC Package for 5G Communication in 65 nm CMOS," 2018 IEEE/MTT-S International Microwave Symposium - IMS, Philadelphia, PA, pp. 1476-1479, 2018.

[25] B. Hassibi and H. Vikalo, "On the sphere-decoding algorithm I. Expected complexity," in IEEE Transactions on Signal Processing, vol. 53, no. 8, pp. 2806-2818, 2005.

[26] J. Choi, J. Mo and R. W. Heath, "Near Maximum-Likelihood Detector and Channel Estimator for Uplink Multiuser Massive MIMO Systems With One-Bit ADCs," in IEEE Transactions on Communications, vol. 64, no. 5, pp. 2005-2018, 2016.

[27] Q. T. Dong, N. Prayongpun and K. Raoof, "Antenna Selection for MIMO Systems in Correlated Channels with Diversity Technique," 2008 4th International Conference on Wireless Communications, Networking and Mobile Computing, Dalian, pp. 1-4. 2008.

[28] Zhi-Pei Liang and P. C. Lauterbur, "Constrained imaging: overcoming the limitations of the Fourier series," in IEEE Engineering in Medicine and Biology Magazine, vol. 15, no. 5, pp. 126-132, 1996.

[29] Lin-Chuan Tsai and Ching-Wen Hsue, "Dual-band bandpass filters using equal length coupled-serial-shunted lines and Z-transform technique," in IEEE Transactions on Microwave Theory and Techniques, vol. 52, no. 4, , pp. 1111-1117, April 2004.

[30] P. J. Nahin, "Behind the Laplace transform," IEEE Spectrum, vol. 28, no. 3, pp. 60, 1991.

[31] A. P. Averchenko and B. D. Zhenatov, "Hartley transform as alternative to Fourier transform in digital data processing systems" 2014 Dynamics of Systems, Mechanisms and Machines (Dynamics), Omsk, pp. 1-4,2014.

[32] A. Bruce, D. Donoho and H. -. Gao, "Wavelet analysis [for signal processing]," IEEE Spectrum, vol. 33, no. 10, pp. 26-35,Oct. 1996.

List of Academic Achievement

(As of February 2020)

種 類 別 (By Type)	題名、発表・発行掲載誌名、発表・発行年月、連名者（申請者含む） (theme, journal name, date & year of publication, name of authors inc. yourself)
Articles in Refereed Journals	○ **<u>Alhasani, Mohammed Mustafa A</u>**; Q. N. Nguyen, Ohta, G.-I , Sato, T. "A Novel Four Single-Sideband M-QAM Modulation Scheme Using a Shadow Equalizer for MIMO System Toward 5G" Communications. *Sensors*, vol. 19, no. 8, pp. 1944-1963, 2019. Masaru Sawada, Q. N. Nguyen, **<u>Alhasani Mohammed Mustafa A</u>**, and Takuro Sato, "OFDM Synchronization System using Wavelet Transform for Symbol Rate Detection" TELKOMNIKA, ISSN: pp 1693-6930 (Accepted, In-press).
Presentation at International Conference	○ **<u>Alhasani Mohammed Mustafa A</u>**, Q. N. Nguyen, T. Sato and G. Ohta, "Four Single-Sideband M-QAM Modulation using Soft Input Soft Output Equalizer over OFDM," 2018 28th International Telecommunication Networks and Applications Conference (ITNAC), Sydney, NSW, pp. 1-6,2018. ○ **<u>Alhasani Mohammed Mustafa A</u>,** Q. N. Nguyen, Gen-Ichhiro Ohta, Masaru Sawada, Takuro Sato, The design and Performance Evaluation of 4-SSB with SISO and Shadow equalizer toward 5G Communication Networks, fifth International Congress on Information and Communication Tech. ICICT 2020 (Accepted, In-press).
Presentation at International Workshop	**<u>Alhasani Mohammed Mustafa A</u>** and Takuru Sato "Four Single Sideband Modulation with High Oder Modulation" WUHU Workshop 2017, Seoul Korea, December 2017.
Award	The outstanding research achievement and contribution to Asia Pacific Society for Computing and Information APSCIT 2019 Annual Meeting (Invited Talk), 07/29/2019, Hokkaido, Japan