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Electrical and Computer Engineering

SPECTRALLY EFFICIENT HYBRID RADIO FREQUENCY AND VISIBLE LIGHT COMMUNICATION BASED ON HERMITIAN SYMMETRY FREE WITH DIRECT CURRENT BIASING

Zahraa Mustafa Zaidan ZAIDAN

Doctor of Philosophy Dissertation

Supervisor

Prof. Dr. Oğuz BAYAT

Istanbul, 2023

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The dissertation titled SPECTRALLY EFFICIENT HYBRID RADIO FREQUENCY AND VISIBLE LIGHT COMMUNICATION BASED ON HERMITIAN SYMMETRY FREE WITH DIRECT CURRENT BIASING prepared by ZAHRAA ZAIDAN and submitted on 28/04/2023has been accepted unanimously/by majority of votes for the degree of PhD in Electrical and Computer Engineering.

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I hereby declare that all information data presented in this graduation project has been obtained in full accordance with academic rules and ethical conduct. I also declare all unoriginal materials and conclusions have been cited in the text and all references mentioned in the Reference List have been cited in the text, and vice versa as required by the abovementioned rules and conduct.

Zahraa Mustafa Zaidan ZAIDAN

Signature

DEDICATION

This work is dedicated to my parents, Mustafa and Faiza, who have always loved me unconditionally and whose good examples have taught me to work hard for the things that I aspire to achieve. To my uncle and aunt, who has been a constant source of support and encouragement during the doctoral program. I am truly thankful for having you in my life. To my husband Saad and my children Mustafa and Karam who have been affected in every way possible by this quest. Thank you. My love for you all can never be quantified. God bless you.

ABSTRACT

SPECTRALLY EFFICIENT HYBRID RADIO FREQUENCY AND VISIBLE LIGHT COMMUNICATION BASED ON HERMITIAN SYMMETERY FREE WITH DIRECT CURRENT BIASING

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To tackle the rapidly increasing demand for Internet services from mobile devices, network convergence is envisaged by integrating various technology domains. A recently proposed and promising strategy to indoor wireless communications is integrating the wireless fidelity (WiFi) and light fidelity (LiFi) namely a hybrid WiFi and LiFi networks (HWLNs). Such type of networks can handle the short comes of each standalone technology such as the spectrum congestion of WiFi and the limited area coverage of LiFi. In HWLNs, the WiFi sub-network follows the IEEE.802.11series standard applying quadrature amplitude modulation with orthogonal frequency division multiplexing QAM-OFDM to support high speed. While LiFi sub-network follows IEEE.802.11bb standard where OFDM-based modulation approaches are applied. In LiFi technology, light emitted diodes (LEDs) are applied as transmitters then only the signal intensity can be used to encode the information. Consequently, the signal needs to be real and unipolar at the input of LEDs. There are few spatialized approaches which account for this, including the most common PAM based discrete multitoned modulation (PAM-DMT) and direct current biased optical OFDM (DCO-OFDM). However, all of them achieve the real signal representation on the cost of halving the spectral efficiency as they impose the Hermitian symmetry. In this work, an optical OFDM approach named Hermitian symmetry free with direct current biasing (HSF-DC) is proposed to increase the spectral efficiency of LiFi subnetwork by 100%. The proposed HSF-DC scheme applies clipping, splitting, and reordering on the pulse amplitude modulation based OFDM (PAM-OFDM) instead of imposing Hermitian symmetry to achieve the real signal representation, then a suitable DC-biasing is added to ensure the positivity of the signal. The energy efficiency of HSF-DC is manifested in the fact that it has the least Peak-to-Average Power Ratio (PAPR) and the best Bit Error Rate (BER) compared with the counterparts. The proposed HSF-DC is then integrated with QAM-OFDM to build a spectrally efficient HWLN with gain of 1.3 over QAM-OFDM/PAM-DMT and QAM-OFDM/DCO. Finally, computer simulations show that the proposed hybrid QAM-OFDM/HSF-DC has the best BER performance over stand-alone QAM-OFDM, hybrid QAM-OFDM/DCO and QAM-OFDM/PAM-DMT.

Keywords: HSF-DC, HWLNs, Spectral Efficiency, BER, Energy Efficiency, PAPR, Hermitian Symmetry.

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ABBREVIATIONS

ACO	:	Asymmetrically Clipped Optical Orthogonal Frequency Division Multiplexing
ASK	:	Amplitude Shift Keying
APA	:	Access Point Assignment
APS	:	Access Points
AWGN	:	Additive White Gaussian Noise
BER	:	Bit Error Rate
CSMA/CA	:	Multiple Access Carrier Sense Multiple Access Collision Avoidance
DB	:	Decibel
DC	:	Direct Current
DCO	:	Direct Current Optical based Orthogonal Frequency Division Multiplexing
EE	:	Energy Efficiency
ERFC	:	Complementary Error Function
FEC	:	Forward Error Correction
FSO	:	Free Space Optical Distance
FFT	:	Fast Fourier Transform
EOV	:	ield Of View
GENSM	:	eneralized Spatial Modulation
GPS	:	lobal Positioning System

HWLNS	:	Hybrid WiFi and LiFi networks
HSF-DC	:	Hermitian Symmetry Free With Direct Current Biasing
ISI	:	Inter Sample Interference
ICI	:	Inter-Channel Interference
IFFT	:	Inverse Fast Fourier Transform
IOT	:	Internet of Things
IM/DD	:	Intensity Modulation/Direct Detection
IR	:	Infrared
IPS	:	Indoor Positioning System
LED	:	Light Emitting Diode
LOS	:	Line of Sight
LB	:	Load Balancing
LIFI	:	Light fidelity
LTE	:	Long Term Evolution
MIMO	:	Multi Input Multi Output
NLOS	:	Non-Line of Site
NDC	:	Non- DC
OFDM	:	Orthogonal Frequency Division Multiplexing
OWC	:	Optical Wireless Communications
OOK	:	On-Off Keying
PSD	:	Power Spectral Density

PLS	:	Physical Layer Security
PSK	:	Phase Shift Keying
GENSM	:	Photodiodes
PPP	:	Poisson Point Process
PAMDMT	:	Pulse Amplitude Modulation Based Discrete Multitoned Modulation
PAPR	:	Peak to Average Power Ratio
QAM	:	Quadrature Amplitude Modulation
QAM-OFDM	:	Quadrature Amplitude Modulation Based Orthogonal Frequency Division Multiplexing
IFFT	:	Quality of Service
RMS	:	Root Mean Square
SE	:	Spectral Efficiency
SINR	:	Signal to Interference- Plus-Noise Ratio
SISO	:	Single Input Single Output
THZ	:	Tera Hertz
UOFDM	:	Unipolar OFDM
VLC	:	Visible Light Communication
WIFI	:	Wireless Fidelity
ZF	:	Zero-Forcing

1. INTRODUCTION

1.1 OVERVIEW

By 2025, there will be more than 75.4 billion mobile devices linked to the Internet worldwide, and that figure is expected to keep rising, reaching hundreds of billions by the year 2030 [1]. Additionally, according to Cisco Systems, more than 80% of Internet protocol traffic will take place as indoors and mobile data traffic will account for 71% [2]. As a consequence, by 2035, entire radio frequency (RF) spectrum will suffer to support the demanded traffic [3]. Visible light communication (VLC) has been proposed as an alternative method of wireless transmission to address the spectrum shortage in RF wireless communication [4]. Data transmission using Light Fidelity (LiFi) technology which is a novel relatively recent technology that can support the high-speed requirement becomes possible by VLC [2]. Data rates of up to 10 Gbps and 300 THz of frequency spectrum can be introduced by LiFi. Additionally, access points (APs) of LiFi can be merged with the lighting infrastructure to create a dual-functional system that serves as both a communication and illumination source simultaneously. Furthermore, many other benefits are also provided by LiFi over its RF counterpart, LiFi has a number of additional advantages over RF, such as a license-free optical visible spectrum, the ability to be used in places where RF is restricted, such as hospitals and the ocean, and the ability to offer security because light is unable to pass though the opaque objects. LiFi, on the other hand, is limited to short ranges, usually a few meters, and is unable to pass through obstacles. An effective solution is to complement the fast data transmission of LiFi with the wider coverage of wireless fidelity WiFi to form a hybrid WiFi/LiFi_network (HWLN) [5]. The concept of HWLN was first mentioned in [6]. After a while, Stefan and Haas integrated LiFi with femtocells [7]. In [8], the author proved that the hybrid networks can achieve performance superior to a standalone LiFi system. Energy efficiency for HWLN has been researched recently. Investigation of the advantages of energy efficiency when applying VLC in HWLN was given by [8]. An analysis of HWLN's energy efficiency is presented in [9], it shows that VLC's AP can be used where illumination is necessary and RF's AP is used otherwise. A study of energy efficiency of HWLN uses VLC's AP when illumination is wanted and uses RF's AP otherwise is given in [10]. Study of the coexistence of HWLN in terms of modulation and medium access protocols is given in [9]. Optimizing of hybrid HWLN is elaborated by [11].The advantages of HWLN application services are listed by [2] such as Internet of Things (IoT), indoor positioning as well as physical layer security.

1.2 SCOPE OF THE THESIS

This thesis' primary objective is to look into ways to make hybrid RF/VLC systems perform better. The spectral efficiency (SE) assessment problem, transmission energy and the Bit Error Rate (BER) performance, peak to average power ratio (PAPR) have been reduced. Such improvements are resulted from the scope of this thesis which is highlighted in the shaded blocks in Figure 1.1.

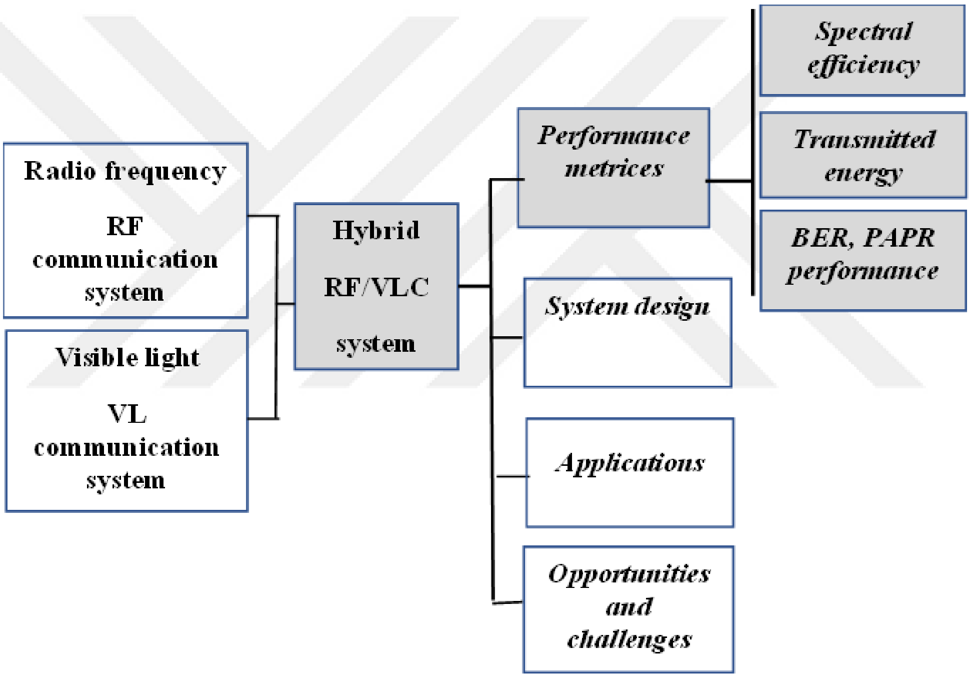

Figure 1.1: Framework of Hybrid RF/VLC System.

1.3 PROBLEM STATMENTS

In RF communication systems, modulation approaches based orthogonal frequency division multiplexing (OFDM) is applied to support high spectral effeicency. Although OFDM is one of the most attractive multicarrier modulation approaches, SE is limited by the spectral efficiency of modulation technique and the number of OFDM subcarriers. To achieve high-speed data rates, RF communication is merged with visible light communication system to build hybrid RF/VLC system. In VLC sub system, simple and low-cost intensity modulation-direct detection (IM/DD) is applied. However, in IM/DD the electric OFDM signal is desird to be real-positive before insertind into the light emmited diode (LED). To produce real and non-negative signals that are compatible with LED characteristics, various optical forms of OFDM-based approaches have been proposed. However, most well known forms generate real signals by forcing the input IFFT data vector to have Hermitian symmetry. To satisfy Hermitian symmetry, the complex signal conjugate must be added before the IFFT, which reduces spectral efficiency by half compared to RF systems, raises PAPR and then deteriorates the BER performance, and doubles the required bandwidth.

1.4 THESIS OBJECTIVES

The purpose of this dissertation is to develope a spectrally enhanced scheme for indoor visible light communication and then integrate it with the radio frequency communication system to build an ificient RF/VLC system that can handle the shortcomes of each stand alone wireless communication system. Verifications of this work is carried out by means of mathamatics modeling, simulation analysis to cover the practical RF/VLC system issues for both the transmitter and the receiver, including spectral efficiency, energy efficiency, PAPR, and BER performance. Developing an improved modulation technique based on OFDM with high spectral efficiency for IM/DD systems. Clipping and rearrangement operations are applied on PAM-OFDM for doubling the spectral efficiency. The proposed OFDM scheme allows to utilizes the whole bandwidth for simultaneous transmission without using the Hermitian symmetry. By clipping half of the PAM-OFDM signal and rearranging the real and imaginary portions of the remaining complex signal, the real representation is obtained and the spectral efficiency is doubled because all the subcarriers are utilized to carry the useful information. An accepted amount of biasing value is added then to ensure the positivity. Comparing the proposed scheme with both asymmetrically clipped schemes and DC-biasing schemes in terms of spectral efficiency, transmitted power, PAPR, and BER performance. Integrating the developed scheme with RF system to build a hybrid network that can takle the performance shortage of stand-alone RFC and VLC systems. Then, comparing the proposed scheme with the related hybrid schemes as well as stand- alone RF communication schemes in terms of BER performance. Mathematical modelling and theoretical derivation of the proposed modulation approach when applied in VLC system and in hybrid RF/VLC system that includes overall system performance such as the spectral efficiency, energy efficiency, PAPR reduction, and BER performance.

1.5 RESEARCH METHODOLOGY

The general methodology of the research is described in Figure 1.2. This thesis investigates the assessment and enhancement of spectral efficiency of VLC system by developing and implementing Hermitian symmetry free scheme with direct current biasing (HSF-DC). In addition, merging the proposed scheme with RF system to build an integrated robust communication network for future high bit rate communication. First, introductory study on wireless communication networks is introduced along with defining and identifying the appropriate metrics for performance assessment. The theoretical modeling for spectral efficiency evaluation, transmitted energy, and BER for both RFC and VLC are discussed and presented. Some works related to hybrid networks issues and IM/DD approaches with advantages and short comes are also summarized. Then, HSF-DC has been proposed to satisfy IM/DD transmission conditions. HSF-DC generates real OFDM signals without using Hermitian symmetry for more utilizing the bandwidth. HSF-DC can further increase the data transmission and hence improve the spectral efficiency of VLC. In addition, integrating the HSF-DC with RF system based on QAM-OFDM to build a reliable promotive communication system. Finally, evaluating the performance metrics of hybrid RF/VLC as well as several comparisons are introduced with conventional hybrid efficient approaches and RF stand-alone system.

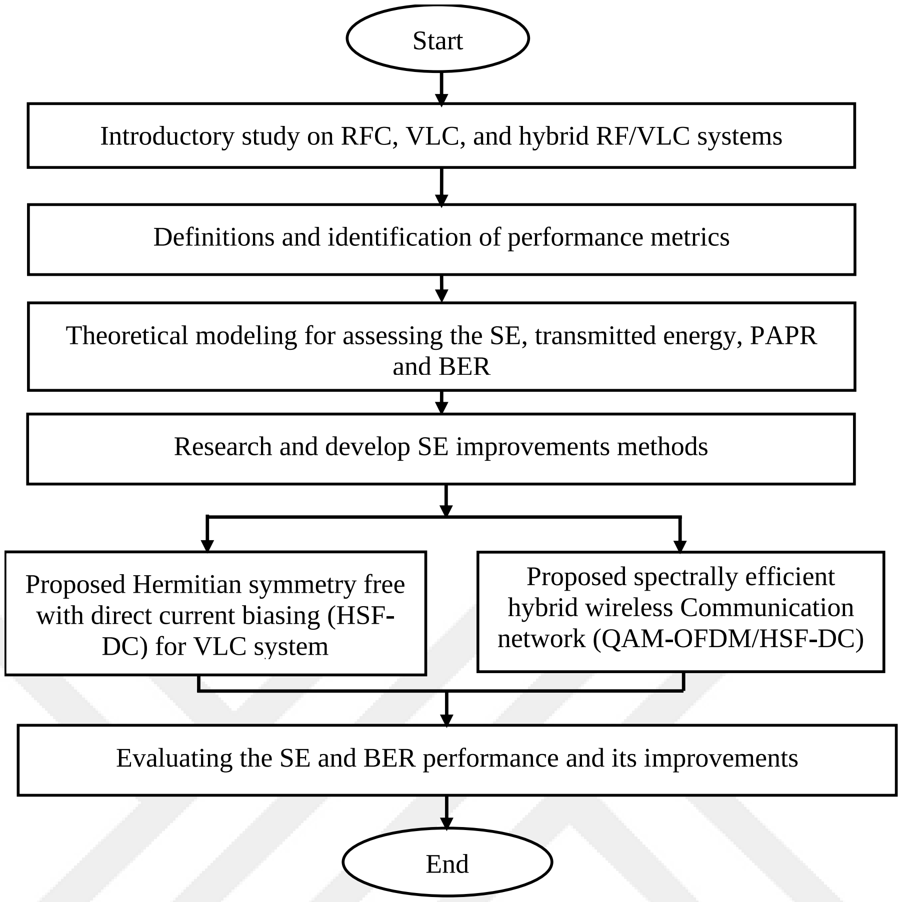

Figure 1.2: General Research Methodology.

1.6 THESIS CONTRIBUTIONS

This thesis addresses the performance of wireless VLC and hybrid RF/VLC systems from SE's perspectives. In particular, the thesis concentrates on assessing and enhancing the SE of indoor communication systems by proposing improved scheme to transmit the PAM-OFDM signals without losing more bandwidth. The research covers the problem of modelling VLC systems and hybrid RF/VLC system including the spectral efficiency assessment and enhancements, and the BER performance enhancements. The proposed model shall serve as the guidance for future system and to be a part of the overall wireless communication solution. This work presents a developed modulation/demodulation scheme named HSF-DC to generate the real signal devoid of Hermitian symmetry, enabling higher spectral efficiency with accepted BER performance in VLC systems. The proposed modulation approach then adds a DC-bias to guarantee the positive signals. The improvements in spectral efficiency, transmitted energy, BER, and PAPR are compared to those of other optical OFDM schemes. The simulation results prove the significant improvement gain in spectral efficiency. Furthermore, the proposed HSF-DC based VLC systems consumes the less amount of transmitted energy, have better BER and PAPR performance. Lastly, theoretical expressions of SE, transmitted energy and BER for HSF-DC have been derived. Next, a spectrally enhanced hybrid RF/VLC is introduced and discussed. This contribution presents an efficient integrated network named QAM-OFDM/HSF-DC to improve the spectral efficiency, energy efficiency, and BER performance. In VLC sub-network, HSF-DC enables to transmit double spectral efficiency compared with the related schemes. In addition, the effectiveness of the proposed system verified by theoretical and simulation analyses as well as the additional capacity gain of spectral efficiency is demonstrated. Detailed performance comparison of QAM-OFDM/HSF-DC with other hybrid networks as well as stand-alone RF network in terms of spectral efficiency and BER schemes is provided for validation purpose. Finally, theoretical expressions of SE and BER for QAM-OFDM/HSF-DC have been derived.

1.7 THESIS LAYOUT

There are five chapters in this thesis. The first chapter explores the overall picture including background, motivations, and general overview. The scope and also the work objectives are introduced in this chapter.

Chapter 2 presents the background of the hybrid RF/VLC communication systems. An overview for RFC and VLC aspects and modulation schemes is introduced. Basic RF modulation approaches based OFDM such as pulse amplitude modulation based orthogonal frequency division multiplexing PAM-OFDM and quadrature amplitude modulation based orthogonal frequency division multiplexing QAM-OFDM are addressed and discussed in details. The chapter further presented and discussed strengths and weaknesses of optical modulation techniques-based VLC systems such as the direct-current-biased optical OFDM (DCO-OFDM), asymmetrically clipped optical OFDM (ACO-OFDM), pulse amplitude modulation based discrete multitoned modulation (PAM-DMT) in details. Some works related to hybrid communication networks and the modulation approaches of IM/DD is also given at the end of this chapter.

Chapter 3 introduces a developed spectrally efficient Hermitian symmetry free scheme to transmit optical OFDM signals. The proposed HSF-DC scheme ensures real signal representation while achieving double spectral efficiency and acceptable BER performance in the VLC system without imposing Hermitian symmetry. The proposed HSF-DC scheme then ensures the positive signals by including a DC-bias, similar to DCO-OFDM. A spectrally efficient VLC sub-system is implemented based on HSF-DC. Theoretical derivatives of SE, transmitted energy, BER, and PAPR are given in this chapter. Then this VLC sub-system is integrated with RF system based on WiFi technology to build a spectrally efficient hybrid WiFi/LiFi network named QAM-OFDM/HSF-DCO. Theoretical derivatives of spectral efficiency and BER is also presented.

In chapter4, the effectiveness of the proposed HSF-DCO is verified by simulation. Comparisons are held with both DC biased scheme no-biasing schemes. Then performance of the proposed hybrid network is also verified and compared with the existed hybrid networks as well as stand-alone QAM-OFDM to prove the improvements and effectiveness of QAM-OFDM/HSF-DCO. Finally, chapter 5 discusses the findings of this study and offers suggestions for future research.

2. WIRELESS COMMUNICATION NETWORKS

2.1 INTRODUCTION

Radio frequency RF wireless communication raised since more than 100 years ago. The data traffic of conventional RF communication continues to expand exponentially. Because smart devices, services, and data-intensive applications are developing so quickly, orthogonal frequency division multiplexing (OFDM) as spectrally efficient multicarrier approach has become very popular to support the demand of high data rates. Although, OFDM is highly attractive modulation techniques, the SE of OFDM is constrained by the spectral efficiency of modulation method and the number of OFDM subcarriers. Day by day, the radio frequency spectrum becomes more congested. This congestion causing spectrum crunch and had adverse effect on the wireless data speed. VLC has recently attracted more attention as a potential complement technology to RF communication owing to its advantages. Large amounts of unregulated frequency band, free licensing, inexpensive front-end devices, and also no interference with sensitive electronic equipment like those in hospital services and airplanes are the main advantages of an optical communication system. Moreover, the current lighting infrastructure can be used also for optical signals transmission, and as long as eye-safety rules are observed, visible light poses no known health risks. [12]. The merits of VLC have been tapped into create LiFi, a full-featured wireless networking system [13]. The LiFi promises to use light emitted diode LED as access points (APs), provide multiuser access with dynamic user associations as well as support bidirectional high data rate communication [14].

This has led to early VLC standardization by three task groups: IEEE 802.15.13, ITU G.vlc and IEEE 802.11bb [2].

Due to OFDM's success in RF, VLC has adopted OFDM as well [15]. VLC utilizes the optical spectrum for wireless data transmission. In VLC, LEDs can be used to transmit the optical signals and photodetectors PDs as receivers. Hence, the signal should be in the form of real and positive. In order to satisfy real OFDM signals, Hermitian symmetry is applied and comes with halving the spectral efficiency of the applied OFDM. This modification is called optical OFDM (O-OFDM). Three forms of O-OFDM can be considered DCO-OFDM, ACO-OFDM, and PAM-DMT. In DCO-OFDM, unipolar signals are achieved by a DC bias which means power inefficiency due to high PAPR. ACO-OFDM modulates the even subcarriers, then clipping at zero and transmits only the positive numbers, thus wasting half of OFDM subcarriers compared with DCO. PAM-DMT converts the real pulse-amplitude modulated signal to imaginary parts and then satisfy the Hermitian symmetry at IFFT, then only transmits the positive parts and has the same performance of ACO [16].

In spite of the high-speed data transmission of VLC, the limited coverage area of LiFi and light blockage are serious problems which is not the case in WiFi as wider coverage is available. In addition, the problem of transmission blockage is reduced highly in WiFi. That's why hybrid WiFi/LiFi networks are proposed as a practical solution for stand-alone LiFi and WiFi challenges. Hybrid WiFi/LiFi networks ensure high-speed data transmission by LiFi and the required covered area by WiFi [15].

2.2 RADIO FREQUENCY WIRELEES COMMUNICATION

The first practical radio system is established in 1895 to transmit radio signals over a distance of 2 kilometres. In 1901, additional experiments are conducted to accomplish radiotelegraph system to transmit telegraphic codes across the Atlantic Ocean over about 1,700 miles. In 1906, the author established the first radio communication system of human speech across a distance of 11 miles. The end of transmitting telegraph codes represents the beginning of the voice-transmitted age [17].

Then, radio-frequency RF wireless communication have been here and there with different applications broad ranging from intelligent home services to satellite communications. As is evident in our daily lives, wireless technologies offer a wide range of features suited for various applications and have been developing quite quickly. More flexibility, efficiency, and lower costs come with less wiring. Wireless communication represents a fast-growing area of communication industry in many parts of the world as it provides a valuable supplement to existing wired networks. Wireless communications become the dominant connection way since the number of users and services subcarriers growing rapidly. Systems which are carried over wires, now can be implemented wirelessly.

2.2.1 Single Carrier Modulation Approaches-Based RF Communication

2.2.1.1 Pulse amplitude modulation (PAM)

The digital PAM's signals can be represented as in the following [18]:

$$S_b(t) = A_b(t)\, P(t), 1 \leqslant b \leqslant M \tag{2.1}$$

where the pulse of duration T is represented by P(t), while $\{A_b, 1 \leq b \leq M\}$ indicates the set of possible amplitudes regarding to $M = 2^k$ possible b-bit blocks of symbols. The amplitudes A_b of the PAM signal have the discrete values:

$$A_b = 2b - 1 - M, b = 1, 2, \ldots., M \tag{2.2}$$

ergy in signal S_b (t) can be calculated by:

$$E_m = \int_{-\infty}^{\infty} A_b^2 P(t)^2\, dt = A_b^2\, E_p \tag{2.3}$$

where E_p is the energy in $P(t)$. The equation above describes the baseband PAM when no carrier modulation. In other case, the PAM signal is a bandpass signal of the form A_b v(t), where both A_b and v(t) are real:

$$S_b(t) = Re[S_b(t)e^{2\pi f_c t j}] \tag{2.4}$$

where f_c is the carrier frequency. The space diagrams of the PAM signals for M = 2, 4 and 8 are given in Figure 2.1[18]. Next equation is used to calculate the BER of one dimensional and two-dimensional M-ary modulation over AWGN channel [19]:

$$P_z = \frac{1}{\log_2 M} \int_{-\infty}^{\infty} A_z\,(x)\, f(x)\, dx \tag{2.5}$$

where $f(x)$ denotes the Gaussian probability density function and A_z (x) indicates the average error bits per symbol corresponding to the noise value x.

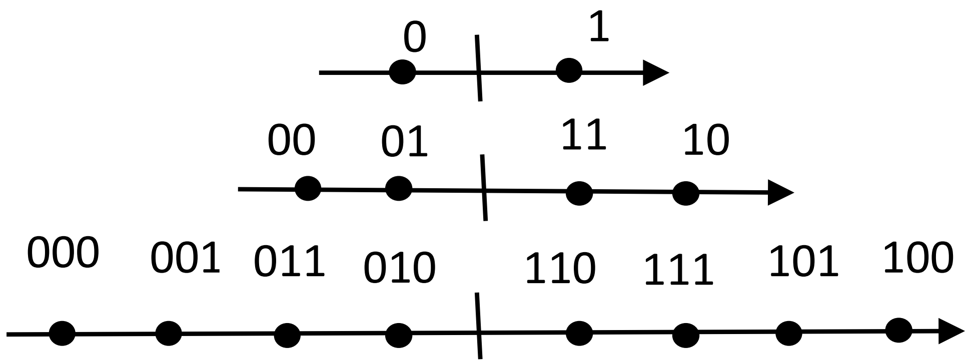

Figure 2.1: Several Signal Spaces Diagrams for PAM.

2.2.1.2 Quadrature amplitude modulation (QAM)

QAM is high-order modulation yielded by combining the amplitude shift keying modulation (ASK) with the phase shift keying (PSK) technique [20]. Mainly, it is applied in main digital systems like telecommunication systems and applications that require high data rates delivery. For applications that demand data rate beyond 8-PSK, it is sensible to shift to QAM as it is feasible to get more space between the neighbouring points in the in-phase/ quadrature plane by evenly distributing the points as shown in Figure 2.2 [18]. However, the challenge is that the demodulators must detect both the amplitude and the phase [21]. Although there are many different QAM formats, the most widely used ones are 16, 64, 128, 256 and 1024 QAM. High orders of QAM are less reliable compared to lower orders [22]. The mathematical form of M-QAM signals is given as in the following [23]:

$$S_j(t) = g(t)\, a_m cos(2\pi f_c t) - g(t)\, b_m sin(2\pi f_c), \qquad m = 1,2, \ldots\ldots, M \qquad (2.6)$$

where $g(t)$ denotes the signal pulse, the independent numbers $a_m$and b_m are chosen according to the precise location of the signal point. Higher modulation order of QAM schemes is vulnerable to error. For this object, error correction coding offers better opportunity to signal to be survived under AWGN and Rayleigh channels then improves the BER performance of the system. Because different applications may require different amounts of power or bandwidth, while the other application may need higher data reception precision than another, there is always a trade-off in the applications. Deciding the suitable modulation method cannot be disregarded since it highly affects the overall the physical accomplishment of the communication systems as a whole. I-ary PAM and I^2-ary QAM both exhibit identical BER performance over AWGN channel, as well as in fading channels [19].

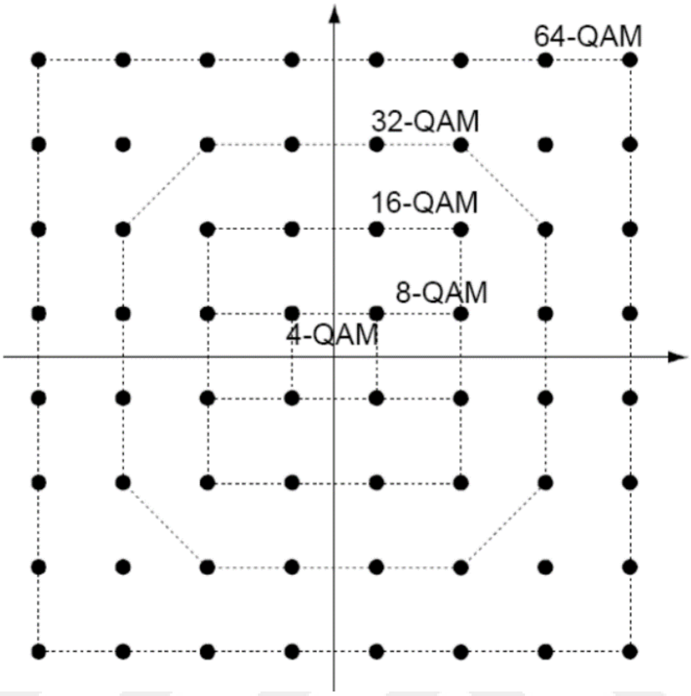

Figure 2.2: Several Signal Spaces Diagrams for QAM.

2.2.2 OFDM Based Wireless RF Communication

OFDM is a key technology that developed gradually and becomes the dominant approach in telecommunication. Today, OFDM employment handles many issues in a wireless communication such as high data rates, eliminate inter symbol interference, and channel equalization [24] [25]. OFDM is a successor of Frequency Division Multiplexing FDM. FDM puts guard band between the carriers in order to prevent overlapping, however such action reduces the spectrum efficiency. While in OFDM, a large number of slowly modulated narrowband closed-spaced subcarriers are created from a high data rate modulating stream, and hence OFDM gets a higher spectrum efficiency compared to FDM [24]. OFDM can work with many technologies such as WiMAX, WiFi, cognitive radio, digital audio and video broadcasting, optical networks. In OFDM, overlapping enables efficient use of the available spectrum. Besides, OFDM is more resistant due to channel division into narrowband flat subchannels. OFDM is more resistant due to channel division into narrowband flat subchannels, by using a cyclic prefix, it can eliminate ISI. Moreover, easier channel equalization is possible. It is sensible to apply maximum likelihood decoding with accepted complexity. OFDM is easily implemented by IFFT/ FFT techniques to perform the modulation /demodulation operations.

Figure 2.3 shows the main three parts of a typical OFDM system: the transmitter, channel and receiver. The transmitted signal in OFDM systems can take the form [24]:

$$\chi(n) = \frac{1}{N}\sum_{K=0}^{N-1} X[K]e^{\frac{2\pi jkn}{N}} \quad k = 0,1,2,\ldots,N-1 \tag{2.7}$$

where N denotes the number of subcarriers and X[K] represents the baseband modulated signal. At the transmitter, the process starts by mapping the incoming data bits and performing the available modulation scheme. Both modulation and mapping operation are implemented based on the channel conditions such as fading spread and Doppler to improve the system performance. The serial to parallel converter used to converts serial bits into parallel stream. The modulated streams undergo baseband OFDM modulation, then the parallel to series converter serializes the parallel bits. Each data symbol has a cyclic prefix added to it to avoid inter-symbol interference. Now, the data is transmitted via the channel. To recover the original bits, the transmitter's processes are reversed at the receiver side.

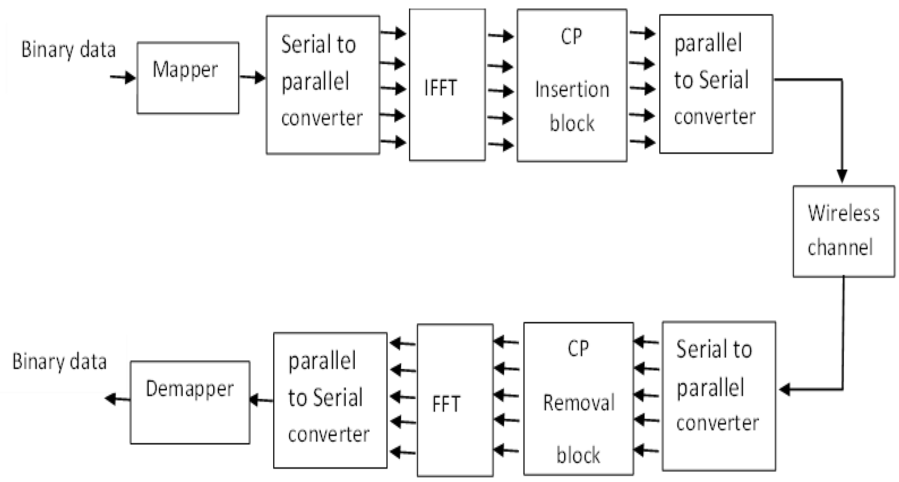

Figure 2.3: Typical OFDM System.

Multiple-Input Multiple-Output technology abbreviated as MIMO is a leap forward in WC system design. MIMO comes with a number of advantages to handle the high data rate challenges as well as high reliability issues due to scarce frequency bandwidth [26]. When the wireless channel is impaired by multi-path fading, the transmitted signal is arrived at the receiver through in equal angles, time delays, and /or different frequency due to the scattering phenomena of electromagnetic waves in the place. Consequently, the power of the received signal fluctuates in time, space and frequency (due to Doppler spread) through the random superposition of the multi-path components which in turns severely affects the performance of the network communication including the quality and reliability.

By considering the advantages of the spatial dimension, the leverages of MIMO are achieved (by providing more than one antenna at the transmitter and the receiver side). In a MIMO system, more reliable data is obtained by transmitting the same massage through more than one antenna over one path. Moreover, the data rates can be increased while extending the number of receive and transmit antennas [26].

In the receiver design, some factors have to be taken into account such as the time synchronization between the arrived signal copies since they travel through different paths, the noise and interference, and also lost signals. A MIMO system enables more signal strength even when there is no clear line-of-site due to utilization of the bounced and reflected RF transmissions .MIMO system offers better quality and quantity of videos due to high throughput.

2.3 OPTICAL WIRELESS COMMUNICATION (OWC)

As shown in Figure 2.4, the optical wireless communication combined two categories. In outdoor environments, OWC is applied to set a point-to-point communication link between buildings. The free space optical distance (FSO) of the links is typically in the mean several kms [27]. Invisible wavelengths of 800 – 1500 nm is used by Infrared IR system [28]. The Infrared Data Association was introduced in 1993, which support the progression of IR products, services and technology [29].

Nowadays, the spectrum of visible optical in the range of 380 – 700 nm is utilized, VLC approach can transmit data by visible light [29]. VLC uses illumination devices, as desk lamps or ceiling light, for transmission [30], [31]. For example, the ceiling light is applied for data transmission to receiver which is typically fixed on a desk in the room. Since we can see illumination devices everywhere, VLC can be used in various applications. VLC consortium in Japan majored the researches on VLC and props the in-progress standardization. In 2011, the VLC Task Group published a VLC standards to define the physical layer for VLC short-range applications [29]. Compared to IR transmission, VLC does not need extra emitters installation because existing illumination is adequate as the lighting devices are already be designed for providing uniform illumination in a room, they can provide good signal coverage. Besides, sources of visible light can supply high intensities, then allow higher SNR compared to IR transmitters which should meet the regulations of eye safety. However, VLC application for instance cannot be applied in aircraft cabin where the light sources must be turned off during the take-off and landing periods. In this scenario, IR transmissions are appropriate. Indeed, OWC can be freely applied worldwide because it never subjects to frequency regulation. The optical signals are restricted by boundaries and cannot pass-through walls. Emitted light beams can be used to detect optical signals. As a result, the transmission range and optical signal propagation is limited to certain areas. Due to this characteristics, multiple optical WLANs can be utilized within the same building or the room with no mutual interference.

Furthermore, the optical signals constriction provides security feature because data transmission cannot be intercept. This is not the case with RF signals that can pass through walls and be picked up outside the areas from which they originate. Besides, OWC systems do not require high frequency circuit design, in contrast to RF systems. Hence, simple transceivers implementation are required for OWC [29]. Optical wireless communication enables vehicle-to-vehicle communications while employing the tail lamps and headlights of vehicles for transmission. Considering that OWC has the potential to significantly relieve RF spectrum, it can be integrated into low-cost, effective transmission schemes for wireless indoor communication and can also be used as a supplement to RF technology. Typically, indoor OWC system employs IM/DD to achieve accepted optical carrier modulation / demodulation. In IM/DD the receiver detects only the optical wave intensity, but not frequency or phase information. Usually, laser diodes LEDs are employed as optical transmitters and photodiodes (PDs) are equipped as detectors.

VLC generally uses the LOS link configuration due to the visible light wavelength. Besides, as white LEDs technologies are improved continuously, white LED is committed to be employed in VLC for providing solid-state illuminating and wireless data transmission simultaneously. Hence, VLC system with white LEDs becomes of actual interest in both industry and academia fields. In VLC systems, White LEDs are typically divided into two groups: blue-chip LED and trichromatic LED.

Since whole electromagnetic spectrum upward 300 GHz is almost crowded. The optical spectrum is used to overcome the congestion of wireless communications. In actual, the optical spectrum exceeds microwave spectrum because it includes the range of 300 GHz to 790 THz [32].

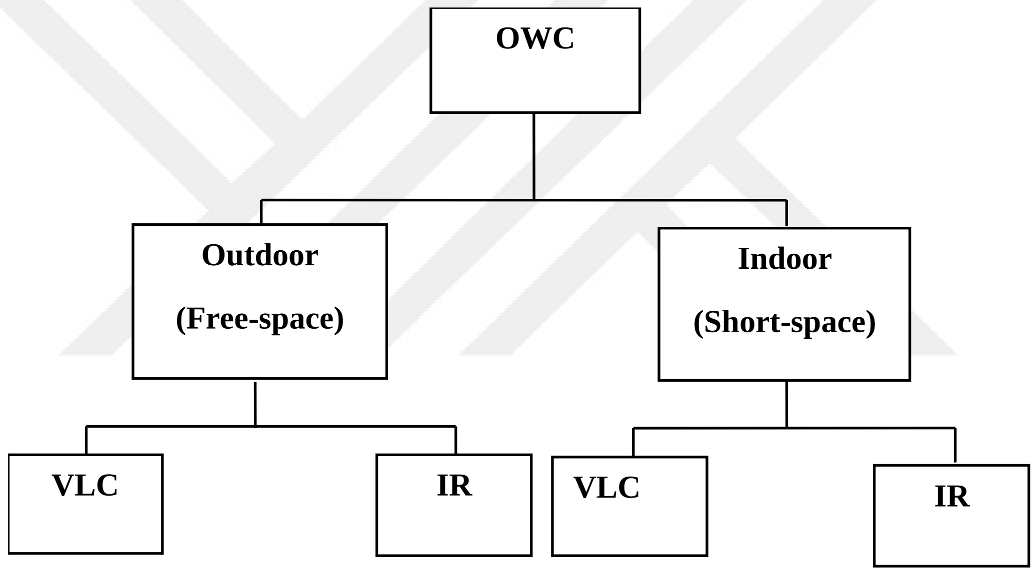

Figure 2.4: Optical Wireless Communications Classification.

2.3.1 Visible Light Communication (VLC)

Today, it has been noticed that there is quite growing research on applying LEDs in VLC systems for lighting and data transmission. The major motive behind this technology interprets the growing currency of solid-state lighting likes high data rate, no health risks, data security, and more power efficiency, LEDs lifetime in comparison with existed sources of artificial light like the incandescent light bulb. The dual functionality achieved by VLC (illumination and communication simultaneously) make it applied for interesting applications, such as high-speed data transmission by lighting sources in offices or the airplane cabins, home networking, car-to-car or in-trains communication, traffic light management. Recently, the power efficiency and reliability levels provided by LEDs exceeds those of the traditional light sources utilized for illumination. Despite of incandescent and compact fluorescent lamp are coasting less than the high-brightness white LED, those are meant to replace, it is anticipated that the prices will decrease considerably with time and broader adoption. In VLC, recent research has successfully allowed data transmission at over (500 Mbps) [33], that means through short links in environments like home and offices. Another research and developments try to find new possibilities to treat some of the issues belongs to the existed infrared, microwave radiocommunication systems, and lighting technologies.

In the future, it is expected to use LEDs as primary illumination source. Thanks to improvements in solid-state lighting, energy consumption is significantly lower compared to the conventional sources. In addition, controlling the brightness and colour of illuminated space is possible. White light illumination is the most popular type where dual functionality is provided. A yellowish phosphor coating and a blue LED can be combined to produce a broad-spectrum white light. Such case has the benefit of low price at the cost of reduced bandwidth; e.g., 3-5 MHz compared with 20 MHz of red, green, and blue LEDs [34], [35]. Several papers reported the possibility achieving high transmission rates [36]. Next generation standards of OWC are currently defined by IEEE 802.15.7r1 to perform data rates at 1 Mbps up to 10 Gbps. In VLC systems, the data rates are limited owing to the response time of the coated phosphorous. A blue filter is positioned at the receiver side to increase the bandwidth up to 20 MHz typically [37], [38]. However, such enhancement comes at the cost of intensity losses by 10 dB. Another alternative proposed solution can be applied such as pre equalization, post equalization, multiple-input multiple-output (MIMO) [27], [39], and finally high-order modulation approaches based on optical OFDM [38]. The data rate can be increased specifically by spatial multiplexing [30]. In indoor VLC, it is interesting to adopt MIMO architectures for increasing the data rate through spatial multiplexing since dramatic channel model is usually applied. The simple way to implement MIMO architecture is to apply an imaging lens at the receiver to collect the incoming signal intensity. However, there is a drawback of channel matrix rank-deficient depending on the receiver position, hence data recovery becomes rather impossible [27]. To sum up, the use of an imaging lens comes at the cost of large size, costly and complex receiver [40]. From all above, optical-OFDM to achieve higher data rate in visible light communication has drawn particular attention.

2.3.2 Optical OFDM Approaches-Based VLC

In [40], author shows the possibility of applying multi-carrier modulation techniques to OWC. Particularly, OFDM is greatly applied as multi-carrier technique for OWC. This is due to bandwidth efficient advantages of OFDM and the ability to handle multipath propagation defections like ISI and with frequency selectivity resulted by the frequency response of LEDs [40]. The wideband channel in OFDM is split up into a number of narrowband sub-channels. In parallel way, the data streams are delivered by the orthogonal sub-carrier channels. These multiplexed channels are summed up by applying an inverse Fourier transformation, then transform the frequency division into a time domain signal. In OWC based on IM/DD, the time domain signal is used for light intensity modulation. To satisfy the IMDD conditions the time domain signal must be positive. Narrowband sub-channels used in OFDM allow less-complex equalization. The OFDM sub-channels are considered as non-frequency-selective channels and individually equalized by a single-tap equalizer in the frequency domain. Both bandwidth and data rate are constrained by multipath which in turns affect the OWC systems performance. However, high data rates are supported by the OFDM technique even in multipath situations. There is a guard interval between the OFDM symbols to handle multipath effects and mitigate ISI. In light of this, OFDM emerges as a strong contender for both widespread and dispersed OWC transmission scenarios since the symbol duration exceeds the delay spread caused by multipath propagation. Additionally, fast Fourier transformation (FFT) and inverse fast Fourier transformation (IFFT) make it simple to implement OFDM an receiver and transmitter respectively [34], [41]. However, because of the high PAPR, OFDM is susceptible to clipping effects. Moreover, inter-channel interference (ICI) and non-linearities largely affect the OFDM performance.

2.3.2.1 Direct-current-biased optical OFDM

As mentioned earlier, inserting the input data stream to the IFFT side in such a way to satisfy Hermitian symmetry generating a real-valued signal. In order to satisfy unipolar signals at the input of LEDs, DCO adds a DC bias level [42]. The DC bias level must be choice appropriately to ensure positivity of the IFFT signals, at the same time keeping lower and upper clipping effects at the minimum [41]. Due to the high PAPR of OFDM signals, a high DC bias may be necessary. As a result, the DCO technique has a low power efficiency, which is thought to be the main drawback.

Figure 2.5 illustrates DCO system. Each bit stream is encoded by M-QAM modulator to complex numbers [43]. The symbols then are re arranged to take a length of N to satisfy Hermitian symmetry, where N means the length of the applied OFDM. Then the signal is inserted into the IFFT to get real signal with positive and negative peaks. A suitable DC bias is then added to the bipolar OFDM signal to make it a positive signal. Due to the Gaussian distribution of the OFDM signal, the negative peaks must be clipped a way. By this step, a clipping noise called n_c is a raised. It affects the system performance and grows as DC bias decreases [44].

$$x(t) = x_0(t) + DC + n_c \quad (2.8)$$

The signal constellation determines the ideal clipping level. Large constellations, such as 256-QAM, necessitate high SNR; as a result, clipping noise must be extremely low and DC bias must be high.

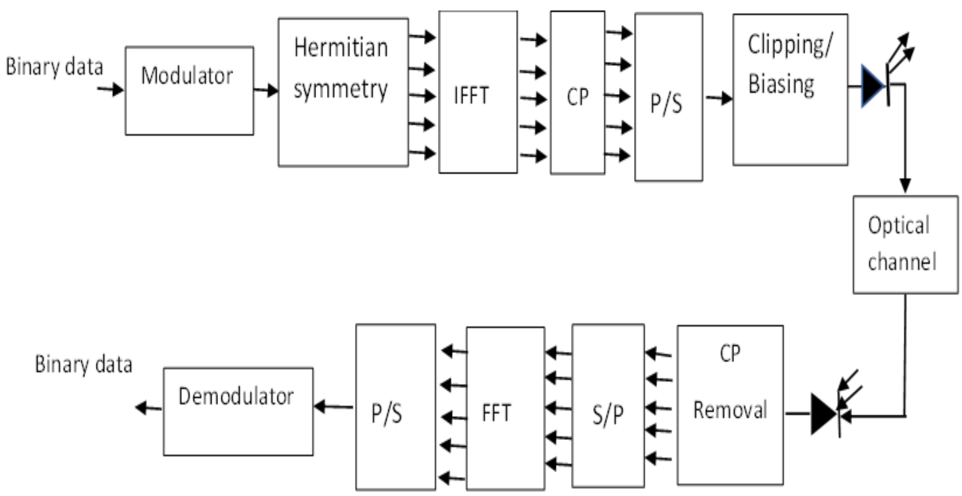

Figure 2.5: System of DCO-OFDM.

2.3.2.2 Asymmetrically clipped optical OFDM

In [41], the authors proposed a power efficient optical modulation method of OFDM.

This scheme is named asymmetrically clipped optical orthogonal frequency division multiplexing ACO. The power efficiency of ACO comes from being DC bias is not necessary to be added, then ACO-OFDM is more power efficient compared to DCO-OFDM. In ACO-OFDM, Hermitian symmetry is also applied to achieve real- signal representation as shown in Figure 2.6 [43]. Only sub-carriers of odd-numbers are modulated while the even sub-carriers are null. The ACO- time domain signal's second half is identical to its first inverted half. Hence, it is possible to clip all the negative parts without destroying the OFDM signal. By this step, the bipolar signal is converted to a unipolar waveform by setting all negative amplitude values to zero. Then there is no restriction for intensity modulation onto the optical carrier. Due to the fact that no data is transmitted at the even subcarriers, the average optical power is decreased. However, since only the odd sub-carriers of the applied OFDM are loaded with data, ACO can only achieve half the spectral efficiency of DCO. In ACO-OFDM, all constellation sizes have the same configuration. In the opposite of DCO-OFDM where combined DC- bias is changed while increasing the constellation size. Due to the Hermitian constraint, ACO-OFDM has N/4 independent complex inputs to N IFFT, which means that for a given constellation, its data rate is half that of DCO-OFDM.

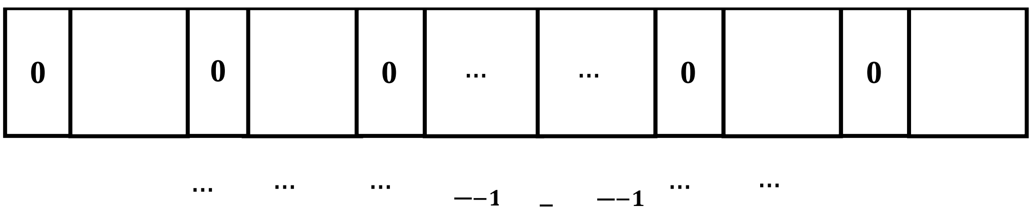

Figure 2.6: Input Vector of ACO-OFDM to IFFT.

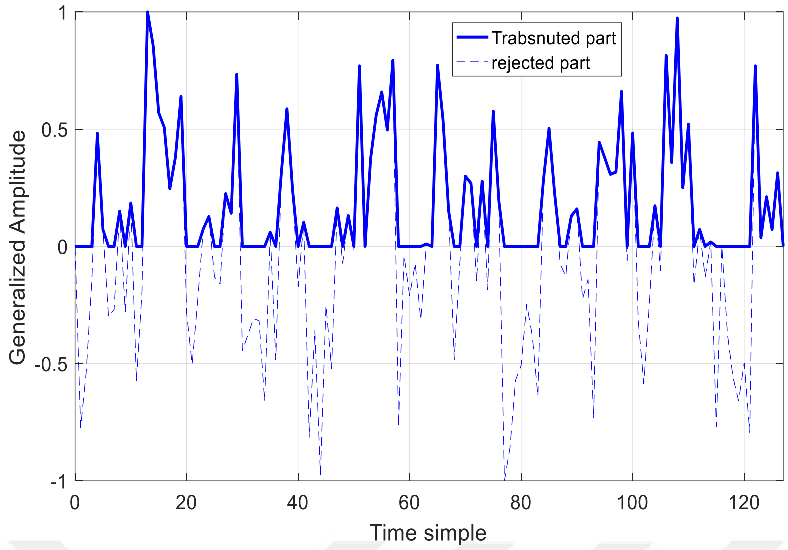

Figure 2.7: ACO-OFDM Time Domain Signal, IFFT Size is 128 and M=16 is Used for QAM Signal Modulation.

2.3.2.3 Pulse-amplitude-modulated discrete multitone modulation

In [45], pulse-amplitude-modulated discrete multitone modulation (PAM-DMT) was proposed. In the contrast to ACO and DCO which use QAM symbols, PAM symbols are employed by PAM-DMT to modulate the sub-carriers [46] as shown in Figure 2.8. The bit streams are inserted to PAM modulator to be mapped due to the chosen constellation of M-PAM. The mapped symbols are then transformed into imaginary form before applying Hermitian symmetry.

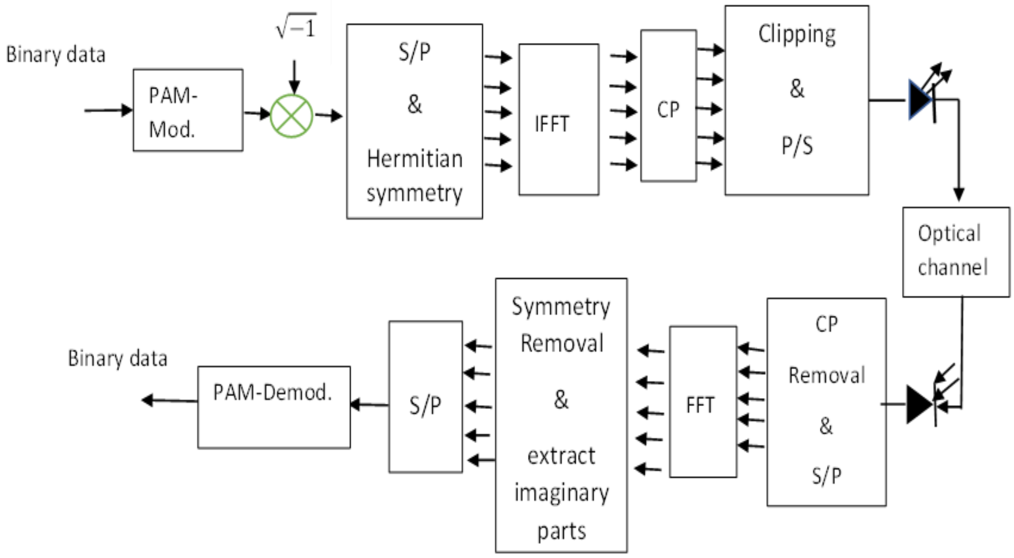

Figure 2.8: System of PAM-DMT.

Figure 2.9 demonstrates the PAM-DMT transmitter's input vector. As illustrated, the imaginary parts are modulated, while the real parts are replaced with zeros, $x_{j} = j\, I_{j}^{PAM}, for\ \left(j = 1,2, \dots \frac{L}{2} - 1\right)$. The PAM-DMT waveform is fully symmetrical in both the positive and negative amplitudes. According to [46], the PAM symbols and the clipping noise are orthogonal.

Moreover, it is noted that PAM-DMT and DCO-OFDM both have the same bandwidth utilization factor [47]. Although the subcarrier utilization of PAM-DMT and DCO is identical, the structure of time domain signal is the same of ACO.

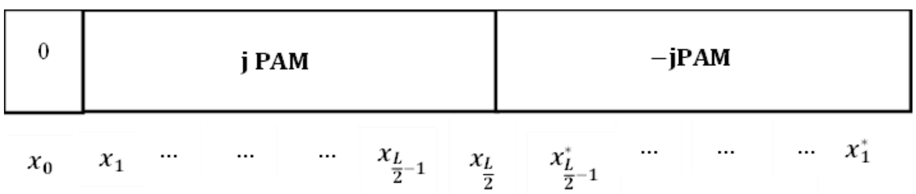

Figure 2.9: Input Vector of PAM-DMT to IFFT of Length L.

2.4 HYBRID WIRELESS COMMUNICATION NETWORKS

Hybrid RF/VLC network was first proposed in [48] . Comparing this type of hybrid network to standalone RF and VLC systems, better performance results can be obtained. Such networks can deliver desired coverage through RF as well as high data rates through VLC. There is no interference between the two integrated systems because VLC uses a different spectrum than RF spectrum. Due to this, hybrid networks outperform standalone VLC or RF networks in terms of system throughput and quality of service (QoS) [4]. Load balancing (LB) mechanism is used in hybrid networks to enhance the overall QoS. To handle user mobility, the LB is made up of access point assignment (APA), resource allocation, and handover management. There have been several studies on the world of hybrid networks. In [48], the system throughput enhancement is studied for the hybrid VLC and RF networks. In that work, user mobility and random device orientation are not considered. In [49], a practical hybrid WiFi /LiFi networks uses LiFi for downlink stream and WiFi for uplink connection. In [50], a different hybrid network is proposed where both of LiFi and WiFi can support downlink and uplink streams. Network hypervisor is needed to ensure flexible resource allocation and link management. The lighting requirements must be followed in the design of the LiFi system. For office environments, the international organization for standardization on lighting specifies illumination levels between 300 and 1500 lx. The positions of the lights in a room were determined by the authors of [37]. Under illumination requirements, LEDs optimization to enhance the performance is not simple. This process includes a set of factors regarding LEDs, inclusive LEDs locations and orientations, emission pattern, output power field of view, colour temperature, etc. The authors in [51] found that the photometric flickering increased for higher data rates. This demonstrates how crucial it is to include a control mechanism in the development of the system to keep flickering at a level that is safe for the eyes and productive.

Table 2.1: Comparative Issues of VLC and RFC.

Issue	Visible light communication	Radio frequency communication
Available spectrum	400 THz	300 GHz
Communication distance	Few meters	10m
Communication topology	Unidirectional and bidirectional	Unidirectional and bidirectional
Data rate	10 Gbps	Up to 8 Gbps
Spectrum	Visible light	Radio waves
Advantages	very fast data transmission, wide variety of applications, large available spectrum, parallel use of lighting and communication, and high security levels	Support for LOS/NLOS communication at high data rates with medium coverage and moderate mobility

2.4.1 Architecture of Hybrid Communication Systems

Generally, there are two basic ways that LiFi can be combined with the current WiFi systems: autonomous and centralized. The first method is to incorporate LiFi into the WiFi autonomous network architecture that already exists. In this method, the user may select an access point (AP) from any network domain, and the AP may utilize any open channel. Although the network complexity is low using this method, the network performance suffers. Otherwise, a central control unit can be used to manage the LiFi and WiFi APs that are owned by the same person. It is possible to produce optimal routing and resource distribution at the network level.

In practical, WiFi APs can provide coverage up to 10 meters inside, whereas LiFi APs typically cover an area of a few meters. To ensure excellent network performance, the LiFi APs—which are typically built into the ceiling lamps—must be positioned properly. The models of hexagon, lattice, and Poisson point process (PPP) are three options for cell deployment [52]. The hexagonal network model is the best type of cellular network. The signal-to-interference-plus-noise ratio (SINR) coverage probability is at its highest in LiFi. The hexagon structure offers an upper bound analysis of performance despite not being as common to find as the deployment of lamps in daily life. Due to its ease of installation, lamp lattice structures are widely used. Most studies involving VLC and HWLNs take this model into account. The SINR coverage probability it can provide is very similar to that of the hexagon model. The PPP structure is appeared to simulate APs with random locations. With this deployment, achieving uniform illumination is difficult. Additionally, of the three models, the SINR coverage probability is the lowest for PPP. For a deployment structure, a trade-off between coverage probability and handover rate is determined by the distance between APs. According to studies, in most situations a 3-meter separation is ideal [53].

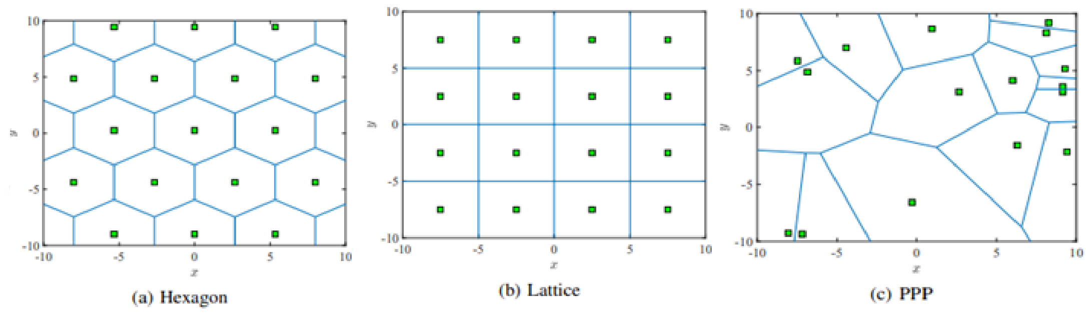

Figure 2.10: Optimized Placements of Lifi APs.

The LiFi and WiFi's multiple access protocols and digital modulation mechanisms have been briefly mentioned in [54]. The current LiFi standards use time-division multiple access (TDMA) and carrier sense multiple access/collision avoidance (CSMA/CA) for multiple access. At any given time, only one link may be active. Inter-cell interference can be effectively decreased with CSMA/CA. However, access for the user is unpredictable, particularly in dense deployments. In addition, LiFi typically uses visible light for downlink and infrared for uplink, unlike WiFi, which uses time division duplex.

2.4.2 Access Types of Hybrid Communication Systems

A hybrid communication networks consists of two or more sub-networks [15]. These networks function in different ways according to the application contexts and kind of networks available. There are several accessible access types:

i. Access both networks at once: The receiver receives the data from both networks at once, increasing the dependability of the communication system.

ii. Access the best connections: The receiver determines the best network from among the available networks.

iii. Use one network's uplink paths and another's downlink paths.

iv. Access based on the kind of application:

Since different applications require different degrees of QoS, that are supported by a variety of networks, the accessible systems are classified based on the application in order to serve specific purposes.

2.4.3 Traffic Distribution in Hybrid Communication Systems

In a hybrid network, a sub- network can be selected based on factors like traffic type, security level, data rates, lighting requirements, uplink/downlink service types, and mobility support. Criteria of the appropriate network selection is addressed in the following:

a. Uplink/downlink transmission

LiFi sub-networks support the downlink while RF sub-networks can support uplink since optical communication systems support higher data rate services than WiFi communication. As a result, massive amounts of traffic can be transferred from RF networks to optical networks, significantly reducing the interference effect.

b. Traffic type

Some services, such as real-time voice and banking, demand low data rates but high levels of quality of service. On the other hand, a small number of traffic types, like video streaming, demand high data rates with low QoS levels.

c. Required level of security

In VLC networks, it is impossible for optical links to penetrate the walls and objects. Consequently, anyone outside the room cannot hack the connection. In contrast to the RF communication links.

d. LOS/NLOS

e. One important factor in choosing a network is to take into account LOS or NLOS. As it is known, optical communication cannot support NLOS connection and connection blockage happened. While RF communication support both LOS and NLOS

f. Mobility support

In hybrid networks, RF subnetworks are able to provide services that are mobile while VLC sub-network cannot support mobility.

2.4.4 Opportunities for Hybrid Communication Systems

Hybrid indoor systems can present users with a variety of opportunities. The following discusses a few of them [15]:

a. Offloading traffic to optical wireless networks

Offloading traffic to VLC networks can improve RF system performance. The performance is highly degraded when signals from neighbouring WiFi APs interfere with each other. RF networks can provide application services that require a high QoS, such as voice, and high mobility. VLC supports static users with low QoS requirements, such as background traffic.

b. Improving reliability

In some situations, when some objects block the link between transmitter and receiver, connection blockage happens. In this case, RF connection can support the connection thereby enhancing the network reliability.

c. improving security:

Wireless optical networks are extremely sensitive to obstructions.; hence, the information cannot pass through walls which in turns improve the security of the system.

d. Interference reduction

Since the RF and VLC networks use different bandwidth range, the connection of the sub networks does not interfere. Hence, offloading the connection from RF to VLC will significantly avoid the interference.

g. Improvement of spectral utilization

Offloading of high data rate traffic services to VLC subnetwork and serve the mobile users by RF subnetwork will enhance the spectral usage.

2.4.5 Performance Metrics of Hybrid Communication Systems

There are many metrics to take into account when assessing the performance of wireless networks. including network capacity, quality of service, BER performance, spectral efficiency, and energy efficiency. This section reviews these metrics as well as studies that are pertinent to HWLNs.

2.4.5.1 Spectral efficiency

The efficiency with which a particular portion of the frequency spectrum is used is referred to as spectrum efficiency. It was investigated in [55] to obtain a spectral efficiency of 4.85 bit/s/Hz with a proposed experimental VLC system. The author of [56] used generalized spatial modulation to achieve a spectral efficiency greater than 10 bit/s/Hz. The researchers in [57] coupled DCO with adaptive bit loading to further improve spectral efficiency and proved a link data rate of 15.73 Gbps. In HWLNs, users may be moved to a different network for greater spectral efficiency. In light of this, HWLNs can significantly increase spectral efficiency compared to running the two independent communication systems, with an increase of 10% to 30% [58].

2.4.5.2 Energy efficiency

although, the area spectral efficiency could be enhanced by expanding the deployment density of APs, but the energy cost consumption also rises quickly. As a result, energy efficiency has taken center stage in ultra-dense networks. Energy efficiency and spectral efficiency are trade-offs because an improved spectral efficiency necessitates more energy per bit. The energy efficiency of VLC systems based on O-OFDM is examined and evaluated in [59]. According to reports, ACO uses less energy than DCO. ACO-OFDM offers spectral efficiency that is less than 2 bit/s/Hz. HWLNs can increase energy efficiency because they allow users to switch between different networks. To maximize the energy efficiency of HWLNs, this property is viewed as an optimization problem of bandwidth and power [60].

2.4.5.3 Bit error rate (BER) performance

One crucial performance metric for assessing the effectiveness of digital communication systems is the bit error rate (BER). The BER is the proportion of incorrect bits to all the bits received during a transmission. BER is used to evaluate fiber optic data systems, Ethernet, and radio data link systems. There are a certain number of received bits with errors for every sequence of transmitted bits. If this is the case, the system's integrity might be in jeopardy. Because of this, it's crucial to test the system's performance, and BER is the best method for doing so. The performance of communication systems, including the transceiver and channel, is assessed using the BER value. Additive white gaussian noise, and multipath fading channel such as Rayleigh and Rician are the general environments where the calculation of BER is straightforward. AWGN model describes the channel where the system is elementary, while multipath models are applied for mobile communication system.

A simple channel model called AWGN is used to describe the impact of numerous random processes in origins. The main source of thermal noise in communications networks is the addition of random signals created by the movement of atoms in the receiver's electrical components. Since the received signal is equivalent to the message signal plus noise, it is referred to as additive. White, on the other hand, refers to the notion that the information system's power remains constant across the entire frequency band. Consequently, the Power Spectral Density (PSD) is stable for all frequencies between -∞ and +∞ and denoted as $N_\circ/2$ Watts/Hz, as shown in Figure below.

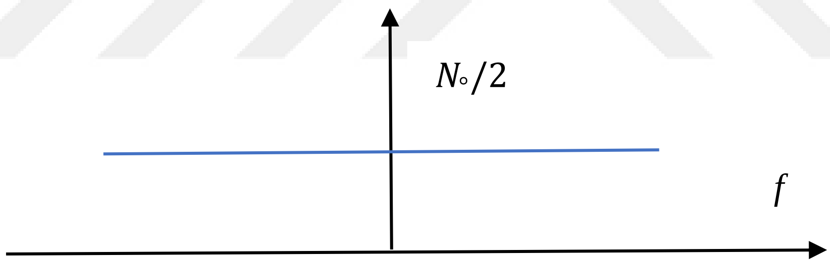

Figure 2.11: Optimized Placements of Lifi APs.

In the time domain, this model has a normal distribution with a mean of zero, and variance as the noise power hence it is Gaussian.

In wireless communication systems, when the signal is transmitted through the channel bouncing off various surfaces until reaching to the receiver producing reflections, scattering, diffraction of electromagnetic.

Consequently, multipath signals are gathered at the receiver. Additionally, when any of transmitter or receiver is in motion, Doppler shift is found. The result is a time-varying, potentially greatly attenuated signal. This is an important flaw in wireless communication systems. The BER can be obtained by averaging the conditional error probability $P_b(\frac{e}{r})$ over the fading channel statistics [19]:

$$BER = \int_0^{\infty} P_b\,(\frac{e}{r})\,P(r)\,dr \tag{2.9}$$

AS P(r) is the pdf of the SNR. Assuming absence of line of sight, the received signal g_r(t) is passed through a Rayleigh fading channel as modeled bellow:

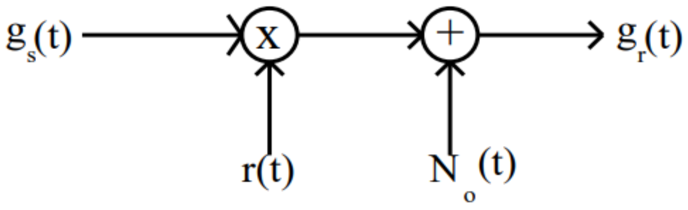

Figure 2.12: Rayleigh Fading Channel Model

where r(t) is the Rayleigh fading and N_o is the AWGN.

2.4.5.4 Network capacity

Network capacity in wireless communication networks is the highest sum data rate that can be supported while still meeting certain requirements. This metric is highly accounted when evaluate the system performance. Integrated scenarios of HWLNs can efficiently increase the networks' capacity when WiFi access points are widely spread. Furthermore, WiFi technology is able to mitigate the capacity deterioration of LiFi due to light-path blockages, as reported in [61]. Massive number of researches has been carried out to maximize the network capacity.

2.4.5.5 Quality of service

At the level of network layer, the data unit is referred to as a packet. Throughput, packet loss ratio, and delay are three metrics for measuring packets that are important for determining the quality of service (QoS). Existing research predicts that indoor wireless networks in the future will be capable of supporting applications with a range of QoS requirements. According to [62], holographic 3D shows require extensive high data rates of above 10 Gbps, whereas automated guided vehicle placement calls for extremely low delay of under 1 ms [62]. The prevalence of IoT is also significantly boosting the number of intelligent devices.

Higher average latency results from more devices on the network, which limits the kinds of applications that high-density WiFi can support.

2.4.6 Challenges Design of Hybrid Communication Systems

The key challenge of HWLNs design is how to effectively integrate the various wireless technologies. The majority of recent studies show that LiFi and WiFi are typically treated as two separate technologies, with network management acting as the primary means of integration. By combining their efforts and achieving a parallel transmission, LiFi and WiFi can overcome the limitations caused by vertical handovers.

2.4.6.1 Cost-effective hardware integration

For HWLNs to be operated, the frond-end components of both WiFi and LiFi are required to be merged on the same board. For signal processing chains, a variety of standard electronic parts are employed, including analogue-to-digital converters, up/down converters, and power amplifiers. It is preferred to share these electronics to reach a compressed and economic hardware design. The main challenges of LiFi and WiFi hardware integration comes from using different antenna components. In order to simulate LiFi and WiFi baseband signals simultaneously, they must be processed within a single signal processing chain. The system gain would be decreased, and more noise would be introduced by this thing.

2.4.6.2 Modulation suitability

Due to restricted available spectrum, the modulation type used for wireless transmissions is crucial. Better communication quality, data security, and information carrying capacity were all benefits of digital modulation [63]. However, there are significant limitations that communication system developers in the industry must deal with, including the available bandwidth, allowable power, and persistent noise level of the system. Other factors like increasing data rates, larger carrier frequencies, higher mobility, and system reliability demanded by users [64]. Digital modulation techniques can offer a number of advantages, such as an increase in the capacity to transmit large amounts of data with noise level immunity. Since bandwidth and time slots are constrained in uplink-downlink communication, the choosing of digital modulation scheme is crucial. Bandwidth and power efficiency are the measuring factors of modulation technique performance. Power efficiency is the capacity of a modulation scheme to keep BER at low power levels, whereas bandwidth efficiency is the capacity of a modulation process to accommodate data by a low bandwidth [63]. Typically, the BER is used to measure the transmission quality. The goal of designing a digital communication system is to achieve the lowest possible error rate and effective channel bandwidth usage. The number of bits passed per second for every Hz of bandwidth is measured by spectral efficiency SE [65]. OFDM is the most popular wireless modulation technology. It uses multiplexing and digital modulation. The explosion of mobile telephone, Internet, and multimedia services combined with a finite radio spectrum is what is driving the need to meet this requirement. The spectral efficiency of an OFDM signal is calculated by multiplying the modulation technique's spectral efficiency by the subcarriers number. The signal to noise ratio (SNR) is the ratio of the system's signal strength to the background noise's amplitude. Shannon's theory of information states that the following equation can be used to calculate the maximum capacity of a channel with bandwidth B, signal power S, and average power of the noise ǯ:

$$S_E = B \log_2(1 + \frac{S}{ǯ}) \tag{2.10}$$

There are a number of potential modulation formats for LiFi, such as OOK, pulse modulation, as well as optical O-OFDM, despite the fact that OFDM is just the most qualified modulation scheme to be applied in the WiFi scenario. Moderate data rates from 1 Mbps to approximately 100 Mbps are made possible by single carrier modulation techniques like OOK and pulse modulation, as well as a comparatively small PAPR. On the other hand, O-OFDM can provide noticeably more data rates but has a high PAPR. The modulation's suitability is determined by the LEDs and PDs used. Practically speaking, the I-V curve's linear zone and bandwidth of commercial LEDs are constrained. Thus, a trade-off between spectral and energy efficiency is established. The PDs have an effect on sensitivity, which has an impact on the link budget. It's critical to research how well LiFi modulation schemes work with practical front ends. Additionally, the best modulation approach will be chosen based on the hardware integration.

2.5 SOME RELATED HYBRID APPROACHES WORKS

In1960s, humanity enter the 'Information Age' with the invention of the Internet. Day by day, people's lives have undergone radical changes with quickly advancement of the Internet technology and more and more connected devices. It is foretold that the amount of internet traffic in 2030 will be 100 times higher than it is present days [66]. This congestion will affect the speed of Internet. Therefore, VLC technology has been addressed as a possible solution to tackle the capacity limitations and RF spectrum congestion. However, VLC technologies can transmit data over only small areas and the optical signals cannot penetrate obstacles. The idea of a hybrid RF and OWC network was first introduced by Rahaim in 2011 [6] as a practical idea to improve data rates and mobility while also optimizing network capacity, signal interference, and power requirements. Then many research trends have been the focus of the researchers such as throughput maximization, QoS and BER performance, load balancing, energy and spectral efficiency, Improved link reliability, resource management, load balancing, and high-data-rate communication, as well as reduced handover overhead.

Soon later, the problem of throughput optimization is researched by [67] wherein the author proposed a model of two independent parallel channels. The same problem is also addressed by author of [68], when an adaptive topology control framework is proposed to meet a given throughput and minimizes the total consumed power. While, the author of [49] proposed a hybrid RF/VLC network with enhanced throughput when VLC serves the downlink and the uplink is served by asymmetric RF/VLC combination to resolve the challenge of maximizing throughput.

Beside the throughput maximizing issue, the performance of hybrid RF/ OWC network is also researched by many authors. In [69], the performance of hybrid networks is studied under Rayleigh fading channel along with derivative of expressions in close form for the outage probability. Analytical expressions of different performance metrics with average symbol error probability (ASEP) were derived in order to enhance the hybrid RF/VLC network's overall performance [70]. Stefan and Haas [58] extended the research by integrating LiFi with femtocells and show that such hybrid networks can perform better than a standalone WiFi or LiFi system. In [71], the author studied and analyzed the performance of hybrid HWLNet and compare it with stand-alone LiFi. Derivatives of SNR and BER are also presented when there is concurrent use of the WiFi and LiFi links.

In hybrid RF/VLC networks, for the connected users to be always served by APs while moving, a dynamic load balancing approaches and hand over mechanisms are of high interesting research areas. In [13], load balancing method is presented to reduce the frequent handover between LiFi APs. A framework for the hybrid WiFi/LiFi system that is practical is investigated in [54], with enhanced throughput and load-balancing between the combined technologies. In [72], vertical handover of hybrid RF/VLC networks is implemented and seamless switching mechanism between two different links is studied. APs selection problem is also discussed in [73]. The fuzzy logic system is developed to decide the group of users that should be served by WiFi. The paper also addresses the differences between heterogeneous and homogeneous in terms of Aps locations. The author of [74] shortly discussed load balancing and hand over strategies in RF/VLC systems. The optimization of hybrid RF/VLC networks is researched by [11]. A study of vertical hand over and load balancing in hybrid RF/OWC wireless system is presented in [75] along with discussion of different issues pertaining to hybrid communication systems.

A more realistic scenario is proposed in [4] to evaluate the hybrid RF/VLC networks by considering the mobility, random orientation, vertical hand over effect. Describing the difficulties in creating hybrid RF/VLC systems, potential promising applications, and future research directions. Comparing the technologies used, network topologies, and key characteristics of all the studies that have been done so far on hybrid RF/VLC networks [13]. The implementation issues for hybrid RF/VLC networks are discussed in [76], such as location determinant of access points resources allocation for load balancing, challenges like user path and mobility, light path obstruction, and handover. In addition, the author classifies in details the modulation techniques of VLC systems into two classes: single-carrier SCM, and multi-carrier modulation techniques. In single carrier modulation, a number of signals transmitted serially with different frequencies and it is suitable for low-to- moderate data rates applications. The simplest modulation approaches are on-off keying (OOK), pulse-position modulation (PPM), and pulse-amplitude modulation (PAM).

The data bits 1 and 0 in OOK are symbolized by turning on and off respective LEDs. It is simple and easy to implemented, mostly adopted by the wireline communication [77]. In 2010, Jelena Vucic proposed the idea adopting OOK in a wireless visible light communication to achieve a data rate of 230 Mbps [78]. Pulse position modulation (PPM) was proposed for VLC [79], wherein the message bits are recognized by the pulses positions. However, PPM suffers from low spectral efficiency. To support dimming requirements, the brightness of the LED is controlled using pulse width modulation (PWM) [80]. Multi-coded Variable PPM, which uses orthogonal codes to code PPM and PWM for data transmission, was proposed for high data VLC networks in 2012 [81]. Pulse amplitude modulation PAM is another simple data modulation scheme, it is easy to be implemented with low computational complexity and PAPR, but it is sensitive to signal distortion [82], [83].

However, inter symbol interference is a significant problem with single carrier modulation (ISI) due to its nonlinearity in the frequency response of VLC channels. Therefore, Optical OFDM (O-OFDM) schemes are generally applied to effectively reduce the ISI and multipath fading, optical power efficiency, and very lower BER [84]. In order for the OFDM signal to be sent by IM/DD, the signal is required to be real and positive. In order to convert the complex signal into a real one, Hermitian symmetry is imposed, while there are number of schemes existed to give the positive form. In 2009, the concept of pulse-amplitude-modulated discrete multitone modulation (PAM-DMT) was presented for the first time to allows the sending of only the positive parts of the signals. Only the imaginary parts of PAM-DMT are modulated with PAM. However, high signal to noise ratio is required because of applying pulse amplitude modulation [85]. Direct current-biased optical OFDM (DCO-OFDM) is one of the most famous optical modulation schemes. DCO ensures the positive form of the transmitted signal by adding suitable DC bias [86]. Another well-known scheme to polarize the signal in the time domain form is asymmetrically clipped Optical OFDM (ACO-OFDM) [86]. Wherein only odd sub-carriers are used to transmit information, which interns reduces the SE by two compared to DCO and PAM-DMT. In 2012, unipolar OFDM (U-OFDM), a novel modulation method, is suggested in [81]. U-OFDM can generate the positive forms by different samples states and new rearrangement of the OFDM to avoid DC adding. However, this operations come with scarifying the SE by half compared to DCO.

In 2013, Non- DC-biased OFDM (NDC-OFDM) is presented for multiple input multiple output (MIMO) scheme in [87]. The new scheme applies spatial modulation to obtain positive and real-valued signals. In comparison to ACO-OFDM and DCO-OFDM, NDC-OFDM can achieve higher spectral efficiency and greater energy efficiency since it doesn't require DC biasing. These improvements, though, come at the cost of additional transmitter and receiver hardware. In 2016, Generalized OFDM- with index modulation IM (GLIM-OFDM), a new optical OFDM scheme for MIMO-VLC systems is suggested by [32]. The new method uses index modulation to create the real signal in order to transmit the complex bipolar signal needed for 4 by 4 MIMO. Index modulation is used to separate and send the real and imaginary components. Both the positive and negative numbers are transmitted in this same way. In contrast to SISO systems, sophisticated equalization is needed, particularly for frequency selective VLC channels.

A hybrid and complex scheme has been proposed in 2013 to improve the SE of IM/DD technique [16]. Asymmetrically clipped DC-biased optical OFDM is the name of the technique the author suggests using to overlay a DCO-OFDM channel onto an ACO-OFDM channel using the odd-frequency subchannels for ACO-OFDM and the even-frequency subchannels for DCO-OFDM (ADO-OFDM). The amount of optical power distributed among the constellations utilized on each component and the DC bias applied to the DCO-OFDM component are two factors that affect how well ADO-OFDM performs. In 2014, another hybrid scheme composes of ACO and PAM-DMT is presented [88]. The ACO-OFDM signal is carried by the odd subcarriers in this scheme, and the even carrier frequencies are used for the pulse-amplitude-modulated discrete-multi-tone signal (PAM-DMT). Hence, there is no need for DC biasing. However, we see a 3 dB degradation for ACO compared to DCO.

In 2015, enhanced PAMDMT is proposed in [89] to enhance the energy efficiency of PAM-DMT. The transmitted data can be loaded on a maximum number of three depths which are hierarchical designed to transform each inter-stream interference signal into the real frequency subcarrier component. However, the resolution of the possible constellation sizes at each depth is limited because the performance of M-PAM is the same as that of M-QAM. Regards to electrical SNR, ePAM-DMT has better energy efficient than DCO-OFDM, while optical SNR is less energy efficient.

A novel O-OFDM modulation scheme for VLC systems is proposed in 2017 [32] and is based on discrete Hartley transform (DHT) and optical spatial modulation (OSM). DHT is utilized rather than DFT. It is possible to use real signal modulated techniques like binary phase shift keying (BPSK) and PAM. Then, using OSM, the real signals are encoded to two (LEDs). Comparing the proposed scheme to NDC-OFDM and GLIM-OFDM, the latter has a lower complexity and improved BER performance. In 2018, a new precoding/decoding algorithm is proposed in [90] for spectral efficient IM/DD system. In the proposed coded modulated optical (CMO) based O-OFDM system, the real OFDM time domain signal is realized by precoding without imposing the Hermitian symmetry. Then, either a DC-bias or the spatial multiplexing technique is used to realize the positive signal. Compared with ACO and DCO, this scheme achieves better BER performance but at the cost of additional components and computations for the encoding and decoding.

In 2020, a triple-layer hybrid O-OFDM (THO-OFDM) for IM/DD systems with an improved spectral efficiency is suggested in [91]. In THO-OFDM, N-points of ACO-OFDM is combined with N/2-point ACO-OFDM, and N/2-PAM-DMT in a one frame to be transmitted simultaneously. Analysis shows that, the proposed THO-OFDM is more spectrally efficient than LACO-OFDM, has lower computational complexity, in addition a 3 dB improvement in the PAPR is achieved compared to LACO-OFDM for the same three layers.

In 2021, a novel layered O-OFDM named DABLO-OFDM is proposed for spectrally efficient schemes to give a controlled adaptive DC biasing which is matching the dimming requirements [92]. The proposed approach uses several layers of subcarriers to increase spectral efficiency while keeping implementation simple. Simulations demonstrate how the proposed scheme outperforms its competitors in terms of achievable spectral efficiency for intermediate dimming and decreased processing latency. By integrating deep learning with traditional OFDM-aided architecture, two novels optical OFDM schemes, LACO-Net and IMDD-OFDM-Net, are proposed in [93]. Both strategies outperform other O-OFDM techniques without learning, such like ACO-OFDM and LACO-OFDM, in terms of BER and PAPR performance. In contrast to the traditional O-OFDM, learning requires a high level of complexity, which is a limitation.

2.6 SUMMERY

A systematic review of wireless communications including radio frequency communication, visible light communication, and hybrid communication networks is given in this chapter along with the detailed background of performance, mainframe work, and applications. The main models and concepts of both RF and VLC modulation approaches are reported.

Simple single carrier modulation procedures like M-PAM and M-QAM are given and explained to show the differences in application requirements of each other. Higher data rates approach like OFDM is also introduced along with advantages and disadvantages. Some details about MIMO principles for both RF and VLC are also given in this chapter to show how it can boost data rates and communication reliability when applied in different procedures.

An overview of OWC is introduced in order to show why it is integrated with RF communication system. Optical OFDM approaches like DCO-OFDM, ACO-OFDM, and PAM-DMT have been explained in detail to show the advantages and disadvantages of each one in terms of spectral and power efficiency. The transmitted signals in IM/DD should be real and non-negative. Such consternate affects the spectral and power efficiency of the mentioned methods due to the use of Hermitian symmetry.

Furthermore, a short description for hybrid RF/VLC systems is given along with description of performance issues such as spectral efficiency, energy efficiency, and BER. Opportunities and challenges of hybrid communication networks are also drawn. Finally, a brief survey about the challenges of hybrid wireless communication networks is presented along with detailed review about the challenges of IM/DD modulation schemes applied for VLC including unipolar and DC biased approaches.

3. EFFICIENT HSF-DC SCHEME MODELLING FOR RF/VLC NETWORKS

3.1 INTRODUCTION

Visible light communication is a rather advanced wireless communication technology that is well appropriate for use in 5G and beyond because it handles the problem of the electromagnetic spectrum's limited availability. [3]. VLC uses the optical spectrum's visible light region between (428 - 750 THz) as a data transmission medium [94]. Special characteristics of VLC, such as its simplicity, low cost, privacy, security, safety, and enormous amount of unlicensed spectrum, make it a strong and promising Key technology for upcoming generations [12], [46]. Additionally, optical radiation in VLC does not obstruct the operation of delicate electronic systems, and backhauling could be accomplished using the current lighting infrastructure [3]. However, the restricted coverage area of VLC serious challenge to be considered. Researchers and manufacturers propose a hybrid network by combining VLC and RF technologies. Hybrid RF/VLC networks allow for quick data transfer from VLC and extensive RF coverage. Such an integrated network can improve upon each connection technology's weaknesses and boost network efficiency. End users can take advantage of the large coverage area that RF systems achieve and the stable rates that optical communication systems offer. Thanks to the hybrid RFC/OWC system, which combines RF and optical based wireless technologies. These networks are realistic because RF and OWC networks can collaborate in the same space, like offices and rooms, without interfering with one another. The availability of wireless connectivity, load balancing, enhanced link reliability, and increased energy efficiency, improved security, and interference reduction are all important functions of hybrid networks.

In hybrid RF/VLC systems, the radio frequency sub-network employs QAM-OFDM in order to increase data rates transmitted over the wireless channels. Motivated by the success of OFDM in RF, OFDM has been adopted in VLC sub network. The transmitted signal must be real and unipolar because most VLC systems use intensity modulation/direct detection (IM-DD). Usually, Hermitian symmetry in the frequency domain is used to produce real OFDM signals. However, using this method results in a loss of 50% of spectral efficiency. [95], in addition to the restrictions imposed by the signal's PAPR, which makes it vulnerable to non-linear distortions. On the other hand, two widely used techniques can be used to satisfy the unipolar constraint: DC-biased and clipping-based solutions [95]. Due to the high PAPR, a suitable DC bias is needed in DC biased OFDM (DCO-OFDM) to obtain the positive signal at the cost of lower power efficiency [96]. Clipping-based solutions, such as asymmetrically clipped optical OFDM (ACO-OFDM), are used to increase power efficiency [90]. However, ACO-OFDM performs poorly in terms of spectral efficiency because it only modulates the odd subcarriers [95] as well as the performance degrades gradually and the scheme becomes in efficient especially while increasing the modulation orders. In order to improve the spectral efficiency as compared to ACO-OFDM and the power efficiency compared to DCO-OFDM, a new scheme identified as Pulse Amplitude Modulated-Discrete Multitone (PAM-DMT) has been proposed. [95], [97], [96]. However, PAM-DMT suffers from very high PAPR and low BER performance compared to DCO. Studies on PAM-DMT have been conducted in recent years, including analyses of nonlinearity [97], PAPR minimization [97], PAM-DMT performance [46], and efficient receiver design [95].

The concept of clipping operation served as inspiration for the new Hermitian symmetry free with direct current biasing (HSF-DC) scheme that is put forth in this chapter. The following are the benefits of the suggested HSF-DC: To obtain real - time signal representation without imposing the Hermitian symmetry, exactly fifty percent of the time domain data symbols are clipped away at the transmitter. As a result, double spectral efficiency is possible. From the other hand, the proposed method allows to achieve same spectral efficiency of related schemes at smaller modulation order size, which means saving in transmission power [98] and reducing the PAPR which in turn reducing the nonlinear distortions of LEDs and the clipping noise .

In this chapter we introduced a spectrally efficient scheme named HSF-DC for IM/DD systems. The proposed scheme is used to implement spectrally efficient VLC sub-system. Next sections of this chapter present the system model of HSF-DC scheme with theoretical derivatives of spectral efficiency, transmitted energy, and BER performance. Then the proposed system has been merged with QAM-OFDM in order to build an efficient hybrid network with improved spectral efficiency and power efficiency. Theoretical derivatives and analyses of performance metrices for hybrid QAM-OFDM/ HSF-DC is also given in details.

3.2 SYSTEM AND CHANNEL MODEL DESCRIPTION OF HWLNS

In hybrid wireless system, when two or more wireless technologies are combined, performance is improved and the limitations of the individual technologies are removed [75]. WiFi and LiFi system convergence or integration results in hybrid systems. In order to facilitate both communication and illumination, VL is employed as the communication medium. A point-to-point or point-to-multipoint communication between transmitters and receivers is possible, as well as a unidirectional or bidirectional connection. VLC is not optimal for outdoor applications because its performance is decreased by ambient light sources and sunlight [75]. Figure 3.1 shows the practical indoor HWLNs, where LiFi AP and a single WiFi AP are installed. In order to manage and connect the LiFi AP and the WiFi through fibers lines, a central unit (CU) is used to manage them. In this model, the user can receive services from either WiFi or LiFi at once, or both [1].

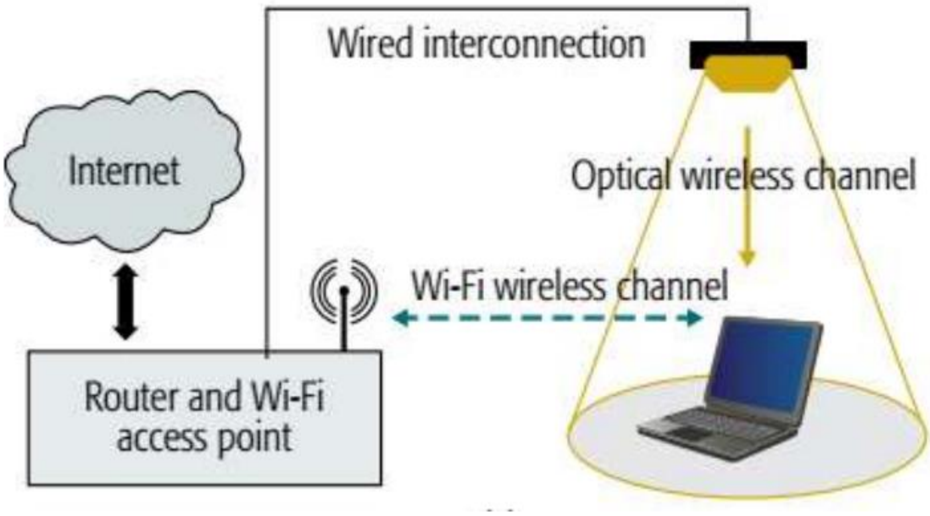

Figure 3.1: System Model of HWLNS.

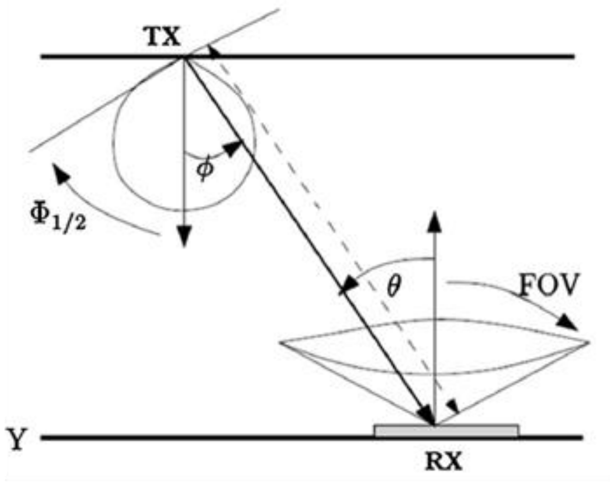

Figure 3.2: VLC Channel Model.

Multiple LEDs are used in each VLC AP to transfer optical signals. To receive optical signals, the user devices are supported by photodiodes (PDs) [73]. Table 3.1 lists the VLC channel parameters. Accordingly, the optical received signal is given by the following:

$$y_v = h_v \, x_v + n_v \tag{3.2}$$

where, x_v is the transmitted signal and n_v is the additive white Gaussian (AWGN) with mean μ and variance σ^2.

$$n_v \sim \text{N}\,(\mu, \sigma^2) \tag{3.2}$$

The LiFi channel impulse response between the transmitter (Tx) and the receiver (Rx) is given by next equation [4]

$$h_v = \begin{cases} \dfrac{(\mathcal{K}+1)A\,\zeta}{2\pi d^2} cos^{\mathcal{K}}(\phi)\cos(\theta) & 0 \le \theta \le \theta_{\frac{1}{2}} \\ 0 & \theta > \theta_{\frac{1}{2}} \end{cases} \tag{3.3}$$

Where d denotes the distance between the LED-PD pair (light emitting diode used like transmitter and photo diode used as receiver), ϕ and θ are the angle of emergence respect to the TX axis and angle of incidence with respect to the RX axis, respectively [94].

With the Lambertian emission order $\mathcal{K} = \frac{\ln(2)}{\ln(\cos(\Phi_{\frac{1}{2}}))}$, where $\Phi_{\frac{1}{2}}$ stands for the LED's semi-angle. The field-of-view (FOV) semi-angle of the PD is $\theta_{\frac{1}{2}}$. While ζ stands for the optical-to-electrical conversion coefficient, which is assumed to be unity, A is the area of the photo-detector (PD) [38].

In the LiFi system, OFDM is applied with different digital modulation schemes. To obtain real signal, Hermitian symmetry is used. Hence, only half of the subcarriers that are available can carry information while the remained are not.

Table 3.1: VLC Channel Simulation Parameters.

Parameters	Values
Room dimensions (W×L×H)	4.0 m×4.0 m×3.0 m
LED position (x; y; z)	(2, 2, 2.5)
PD position (x; y; z)	(2, 2, 2.5)
Viewing angle of luminary	50°
FOV semi-angle of receiver	50°
Area of PD	1 cm^2

In a WiFi system scenario, if the transmitted signal x_r is sent through free space to a receiver at distance d where there are no obstacles in its path. Line-of-sight (LOS) channel is the channel model used for this transmission, and the received signal is modeled as [71]:

$$y_r = h_r\, x_r + n_r \tag{3.4}$$

where h_r is the RF channel gain and n_r is the AWGN. The channel gain is given by [99]:

$$h_r = \frac{\rho\sqrt{Al}\;\, e^{-j2\pi d/\gamma}}{4\pi d} \tag{3.5}$$

where $\sqrt{Al}$ is the result of the radiation patterns produced by the transmit and receive antenna fields in the LOS direction. The wave travels a distance d, which causes a phase shift of $e^{-j2\pi d/\gamma}$, and λ = c/fc indicates the signal wavelength (c = 3 ×10^8 m/s defined as the speed of light).

3.3 SYSTEM MODEL OF THE PROPOSED HSF-DC

The block diagram of HSF-DC system is displayed by Figure 3.3. After a stream of binary bits which is denoted by **u** has been modulated by PAM modulation, the time-domain signal is given as [96]:

$$x(n) = \frac{1}{N}\sum_{K=0}^{N-1} X(k)\, e^{\frac{2\pi\, k\, nj}{N}} \quad k = 0,1,2, \ldots, N-1 \tag{3.6}$$

where $X(k)$ are real-valued symbols which are Pulse-amplitude modulated (PAM) with useful data, N is the inverse fast Fourier transform (IFFT) length.

The following presents a discussion for the proposed scheme. From (3.6), $x(n)$ exhibits a symmetry; since $x[n] = x[N-n]^*$. In effect, clipping away the second half of the signal denoted by x_{nB} will not discard any useful data since the same information can be recovered from the remained half x_{nA}. This means, only half of the PAM-OFDM signal will be sent to convey all the information.

To satisfy the real constraint, the transmitted signal x_{nA} is subjected to a simple transformation to obtain its real representation. Simply, the imaginary parts of x_{nA} are separated and loaded with the same arrangement in place of x_{nB}. Now, the generated real signal is composed of two combined sub frames transmitted simultaneously. The first one holds the real part of x_{nA} with length of $\frac{N}{2}+1$. In the context of this work, this will be referred to as $x_{nA,R}$. While the second sub frame holds the imaginary part. This frame is referred to $x_{nA,I}$ with length of $\frac{N}{2}-1$, because Imag ($x[0]$) = Imag ($x[N/2]$) $= 0$. Later, a suitable DC bias B_{DC}, is added to guarantee the signal to be unipolar for driving LEDs. In practice, B_{DC} is set relative to the power of x **:**

$$B_{DC} = à\sqrt{E\{x^2\}} \qquad (3.7)$$

where: x is the OFDM signal in time domain, and E { ▪ } means statistical expectation, à is the ratio of the DC shift and the standard deviation. This is defined in the same work as a bias of $10\ log10$ (à^2 $+ 1)\ dB$.

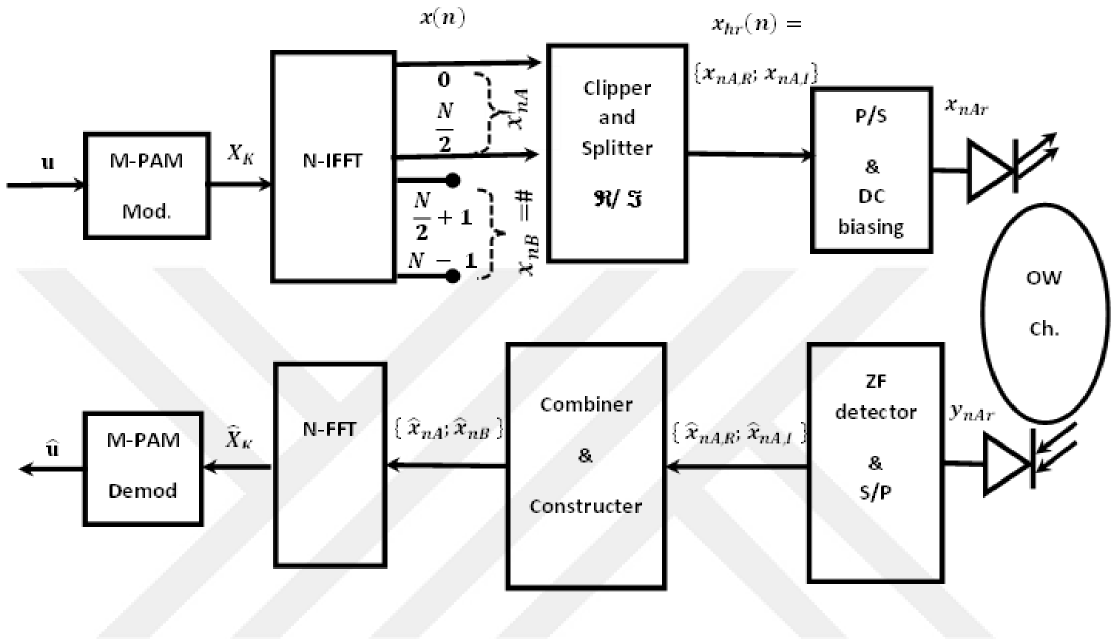

Figure 3.3: HSF-DC Based VLC System Schematic Diagram.

Then, the unipolar signal travels though optical wireless channel. At the receiver, the estimation of x is obtained by using a zero-forcing (ZF) equalizer and is expressed as:

$$\hat{x} = h^{-1}\, y \qquad (3.8)$$

After this operation, the combiner at the receiver side simply adds $\hat{x}_{nA,R}$ for($0 < n < \frac{N}{2}$) $with\ \hat{x}_{nA,I}$ together to recover the complex $\hat{x}_{nA}$ signal, as Imag ($x[0]$) $=$ Imag ($x[N/2]$) $= 0$. Afterwards, constructer comes with $\hat{x}_{nB}$ by flipping the conjugate of $\hat{\boldsymbol{x}}_{\boldsymbol{nA}}$. Finally, the PAM-OFDM demodulation is applied, and the resulted signal would be identical to the original bipolar.

3.4 STAND-ALONE VISIBLE LIGHT COMMUNICATION SYSTEM BASED ON HSF-DC

3.4.1Theoretical Analysis of HSF-DC

3.4.1.1 Spectral and power efficiency analyses

In PAM-DMT and DCO, for a specific modulation index *M*, the spectral efficiency in (bps/Hz) is defined as [94]:

$$\eta_{PAM-DMT\&DCO} = \frac{log_2\,(M)\,(N\, -\, 2)}{2\,N} \tag{3.9}$$

where $\log_2(M)$ identifies how many bits are used in M-PAM and M-QAM constellations, the FFT length is N. The DC subcarriers are set at zero, and just 50 percent of the sub - carriers are modulated as part of the Hermitian symmetry necessity to satisfy real signal, which causes the factor (N − 2) / 2 to appear. For ACO, in order to obtain real and unipolar signal quarter the number of IFFT subcarriers are used to carry data [3]:

$$\eta_{ACO} = \frac{log_2\,(M)\,(N\, -\, 2)}{4\,N} \tag{3.10}$$

While in the suggested method, Hermitian symmetry is not necessary, thus, the data is transmitted using all of the OFDM subcarriers, and the spectral efficiency of HSF-DC can be expressed as:

$$\eta_{HSF-DCO} = \frac{log_2\,(M)\,(N\, -\, 2)}{N} \tag{3.11}$$

for the same modulation index *M*, the spectral efficiency gain of HSF-DC over PAM-DMT, DCO and ACO schemes can be expressed as:

$$\alpha_{\eta 1} = \frac{\eta_{\mathrm{HSF-DC}}}{\eta_{PAM-DMT\&DCO}} = 2 \tag{3.12}$$

$$\alpha_{\eta 2} = \frac{\eta_{\text{HSF-DC}}}{\eta_{ACO}} = 4 \tag{3.13}$$

where $\alpha_{\eta 1}$ represents the spectral efficiency gain of HSF-DC over PAM-DMT or DCO, and $\alpha_{\eta 2}$ is the spectral efficiency gain of HSF-DC over ACO. On the other hand, the proposed HSF-DC can achieve the same spectral efficiency of PAM-DMT, DCO and ACO at reduced modulation order as derived below:

$$M_{PAM-DMT\&DCO} = \left(2^{\frac{2\,\eta\, N}{(N-2)}} \right) \approx 2^{2\,\eta} \tag{3.14}$$

$$M_{ACO} = \left(2^{\frac{4\,\eta\, N}{(N-2)}} \right) \approx 2^{4\,\eta} \tag{3.15}$$

$$M_{\text{HSF-DC}} = \left(2^{\frac{\eta\, N}{(N-2)}} \right) \approx 2^{\eta} \tag{3.16}$$

Hence, simply one can conclude that:

$$M_{PAM-DMT\&DCO} = M_{\text{HSF-DC}}^{2} \tag{3.17}$$

$$M_{ACO} = M_{\text{HSF-DC}}^{4} \tag{3.18}$$

where $M_{PAM-DMT\&DCO}$, M_{ACO} , and $M_{\text{HSF-DC}}$ are the modulation indexes of PAM_DMT & DCO, ACO, and HSF-DC respectively for a given spectral efficiency η.

According to (3.17, and 3.18), the proposed HSF-DC effectively reduces the average energy per bit E in (joule /bit). The energy of the bipolar signal for each scheme can be calculated by the following [18] :

$$E_{\text{PAM\_DMT}} = \frac{M_{PAM\_DMT}^{2} - 1}{6\,log_2\left(M_{PAM\_DMT}\right)} . \varepsilon_g = \frac{M_{HSF-DC}^{4} - 1}{6\,log_2(M_{HSF-DC}^{2})} . \varepsilon_g \tag{3.19}$$

$$E_{(DCO)bipolar} = \frac{M_{DCO} - 1}{3\,log_2\left(M_{DCO}\right)} . \varepsilon_g = \frac{M_{HSF-DC}^{2} - 1}{3\,log_2(M_{HSF-DC}^{2})} . \varepsilon_g \tag{3.20}$$

$$E_{ACO} = \frac{M_{ACO} - 1}{3\, log_2\,(M_{ACO})} . \varepsilon_g = \frac{M_{HSF-DC}^4 - 1}{3\, log_2(M_{HSF-DC}^4)} . \varepsilon_g \tag{3.21}$$

$$E_{(\mathrm{HSF-DC})bipolar} = \frac{M_{HSF-DCO}^2 - 1}{6\,(2 \times\, log_2(M_{HSF-DC}))} . \varepsilon_g \tag{3.22}$$

where ε_g are the energy in real-valued signal pulse g(t) of duration T.

The saving energy factor of the proposed system over PAM-DMT can be calculated as in the following:

$$\alpha_{E_1} = \left(1 - \frac{E_{HSF-DC}}{E_{\mathrm{PAM\_DMT}}}\right) \times 100\% \tag{3.23}$$

$$\alpha_{E_1} = 1 - \left(\frac{M_{HSF-DC}^2 - 1}{6\, log_2(M_{HSF-DC}^2)} . \varepsilon_g \times \frac{6\, log_2(M_{HSF-DC}^2)}{(M_{HSF-DC}^4 - 1) . \varepsilon_g}\right) \times$$

100%

$$\alpha_{E_1} = \left(1 - \frac{M_{HSF-DC}^2 - 1}{(M_{HSF-DC}^4 - 1)}\right) \times 100\%$$

$$\alpha_{E_1} = \left(1 - \frac{2^{2\,\eta} - 1}{2^{4\,\eta} - 1)}\right) \times 100\%$$

$$\alpha_{E_1} = \left(\frac{2^{4\,\eta} - 2^{2\,\eta}}{2^{4\,\eta} - 1)}\right) \times 100\% = 99\%\ when\ SE > 3bps/HZ$$

The saving energy factor of the proposed system over DCO can be calculated as following:

$$\alpha_{E_2} = \left(1 - (\frac{M_{HSF-DC}^2 - 1}{6\, log_2(M_{HSF-DC}^2)} . \varepsilon_g \times \frac{3\, log_2(M_{HSF-DC}^2)}{M_{HSF-DC}^2 - 1) . \varepsilon_g}\right) \times 100\% \tag{3.24}$$

$$\alpha_{E_2} = \left(1 - (\frac{3\, log_2(M_{HSF-DC}^2)}{6\, log_2(M_{HSF-DC}^2)}\right) \times 100\%$$

$$\alpha_{E_2} = 50\%$$

The saving energy factor of the proposed system over ACO can be calculated as following:

$$\alpha_{E_3} = \left(1 - (\frac{M_{HSF-DC}^2 - 1}{6\, log_2(M_{HSF-DC}^2)}.\varepsilon_g \times \frac{3\, log_2(M_{HSF-DC}^4)}{(M_{HSF-DC}^4 - 1).\varepsilon_g}\right) \times 100\% \tag{3.25}$$

$$\alpha_{E_3} = \left(1 - \frac{M_{HSF-DC}^2 - 1}{(M_{HSF-DC}^4 - 1)}\right) \times 100\%$$

$$\alpha_{E_3} = \left(\frac{2^{4\,\eta} - 2^{2\,\eta}}{2^{4\,\eta} - 1)}\right) \times 100\% = \alpha_{\boldsymbol{E}}$$

From other hand, HSF-DC can effectively reduce the PAPR as compared to PAM-DMT, DCO and ACO because avoiding Hermitian symmetry and using lower modulation order led to PAPR reduction [100]. The peak-to-average power ratio is defined as:

$$PAPR = \frac{\max|x(n)|^2}{\mathrm{E}|x(n)|^2} \tag{3.26}$$

where $\max|x(n)|^2$ is the OFDM signal's maximum peak power and $\mathrm{E}|x(n)|^2$ is the signal's average power ratio.

3.4.1.2 Theoretical BER analysis

In digital communication, the average signal to noise ratio (SNR) is defined as the basic of the bit error probability performance; $SNR = \frac{E_b}{N_o}$,where E_b represents the average bit energy, and N_o denotes the noise energy density. In HSF-DC, due to the fact that the recovering of clipped samples doubles the Additive White Gaussian Noise (AWGN) variance at each resulting point, then: $SNR_{HSF-DC} = \frac{E_b}{2\,N_o}$. Based on BER performance derivative of PAM-OFDM introduced in [19], then BER performance of HSF-DC can be expressed as:

$$BER = \frac{1}{log_2\,(M)} \sum_{m=1}^{M-1} C_m^M\, erfc\left((2\,m - 1)\sqrt{\mu_\rho\, SNR_{HSF-DC}}\right) \tag{3.27}$$

Where M indicates the modulation level order, and C_m^M coefficients values are mapped in table I of [19] , $erfc$ is the complementary error function, while $\mu_\rho = \frac{3\, log_2\,(M)}{(M^2-1)}$.

3.5 THE PROPOSED HYBRID (QAM-OFDM/HSF-DC) COMMUNICATION NETWORK

3.5.1 Theoretical Analysis of Hybrid QAM-OFDM/HSF-DC

3.5.1.1 Spectral efficiency

The Hermitian symmetry that is required for intensity modulation and direct detection reduces the spectral efficiency of VLC systems to half that of RF communication systems. We propose to merge the spectrally efficient stand-alone VLC network based on HSF-DC which was mentioned previously in this chapter with WiFi system in order to produce a spectrally efficient hybrid network. In the proposed hybrid network, at an M modulation order the sub systems can achieve equal spectral efficiency.

Generally, when the RF and VLC subsystems operate concurrently to transmit information the total SE is described as in the following:

$$\eta_{\mathrm{RF/VLC}} = \eta_{\mathrm{RF}} + \eta_{\mathrm{VLC}} \tag{3.28}$$

In the proposed hybrid network, WiFi is served by QAM-OFDM due to its efficiency in transmission energy and best BER performance. The SE of QAM-OFDM can be calculated as bellow [3]:

$$\eta_{\mathrm{RF}} = \frac{(N\ -\ 2)}{N}\ log_2\left(M_{QAM}\right) \tag{3.29}$$

where N is IFFT length and M_{QAM} is the constellation order of QAM.

For conventional QAM-OFDM /VLC systems, where DCO or PAM-DMT is used to perform optical modulation, the overall SE can be calculated as bellow:

$$\eta_{\mathrm{QAM-OFDM\ /(DCO,or\ PAM-DMT)}} \cong \left(log_2\left(M_{QAM}\right) + \frac{1}{2}\ log_2\left(M_{DCO,PAM-DMT}\right)\right) \tag{3.30}$$

From the above equations, we note that in hybrid networks, the spectral efficiency of VLC sub-networks is lower than the spectral efficiency of RF subnetwork. In the proposed hybrid network QAM-OFDM/HSF-DC. The enhanced HSF-DC can achieve the same spectral efficiency of QAM-OFDM for the same modulation order. The SE of hybrid QAM-OFDM/HSF-DC can be calculated as bellow:

$$\eta_{\mathrm{QAM-OFDM/HSF-DC)}} \cong log_2\left(M_{QAM}\right) + log_2\left(M_{HSF-DC}\right) \tag{3.31}$$

From the above equation we calculate the spectral efficiency gain of the QAM-OFDM/ HSF-DC over QAM-OFDM/DCO and QAM-OFDM/PAM-DMT as:

$$\alpha_\eta = \frac{\eta_{\mathrm{QAM-OFDM}/HSF-DC}}{\eta_{\mathrm{QAM-OFDM\ /(DCO,or\ PAM-DMT)}}} \cong 1.33 \tag{3.32}$$

3.5.1.2 Energy efficiency

From [18], the overall energy average E of the hybrid network can be calculated as the following :

$$E_{Hybrid} = \frac{(E_{RF} + E_{VLC})}{2} \tag{3.33}$$

The average energy per bit of QAM-OFDM/HSF-DC is given by:

$$E_{QAM-OFDM/HSF-DC} = \frac{1}{2}(E_{QAM} + E_{HSF-DC}) \tag{3.34}$$

The unipolar signal of DC biased signals calculated by [100], [101]:

$$E_{uipolar} = E_{bipolar} + (B_{DC})^2 \tag{3.35}$$

Since it is already shown that energy average of the bipolar HSF-DC is half than that energy average of the bipolar DCO. At the same DC bias value, it is easy to conclude that the energy average of unipolar form of HSF-DC is also half than the energy average of unipolar DCO signal when applying. This is due to the fact that (B_{DC}) is calculated according to the root mean square of the bipolar signals. Hence (3.34) can be written as in the following:

$$E_{QAM-OFDM/HSF-DC} = \frac{1}{2}(\varepsilon_g(\frac{M_{QAM} - 1}{3\,log_2(M_{QAM})} + \frac{M_{HSF-DC}^2 - 1}{6\,(2\times\; log_2(M_{HSF-DC}))}) \qquad (3.36)$$

In hybrid HWLNs, each SE > 4 bps/Hz can be achieved by different modes of the combined modulation orders for RF and VLC (M_{RF}, M_{VLC}). Table 3.2 shows the possible modes to achieve SE = 4, 5, 6, 7 and 8 bps/HZ. It is shown that the same M_{QAM} is applied in all the hybrid networks QAM-OFDM/HSF-DC, QAM-OFDM/DCO, and QAM-OFDM/PAM-DMT. In this case, there is no energy gain achieved by RF sub network for one hybrid network over the others and the overall energy gain can be achieved by the VLC sub-network.

Table 3.2: Modulation Order Modes of Hybrid Communication Networks.

η	modes of hybrid RF/ HSF-DC(M_{QAM}, M_{DC-PAM})	$(M_{QAM}, M_{DCO,or\ PAM-DMT})$ modes of hybrid ((RF/DCO) or (RF/DMT))
4	(4,4)	(4,16)
5	(4,8), (8,4)	(4,64), (8,16)
6	(4,16), (8,8), (16,4)	(4,256), (8,64), (16,16)
7	(4,32), (8,16), (16,8), (32,4)	(4,1024), (8,256), (16, 64), (32,16)
8	(4,64), (8,32), (16,16), (32,8), (64,4)	(4,4096), (8,1024), (16, 256), (32,64), (64,16)

3.5.1.3 Theoretical Probability of Bit Error Rate Calculations

BER is primary metric used to assess the O-OFDM system's performance. The average signal to noise ratio SNR is defined as basic of BER performance. In HSF-DCO approach, the signal is affected by double noise variance compared to the conventional PAM-OFDM then, SNR_{HSF-DC} becomes $\frac{E_b}{2N_o}$. This value is entered into the well-known BER performance formula of M-PAM. Accordingly, equation (3.27.) can be used to calculate the performance of the HSF-DC. For RF sub-system, QAM-OFDM scheme is applied to transmit data with

$$BER_{QAM-OFDM} = \frac{2}{k}\left(1 - \frac{1}{\sqrt{M}}\right) erfc(\mu_Q \, SNR) \tag{3.37}$$

Where M indicates the modulation level order, $k = \log_2 M,\ and\ \mu_{Q=} \frac{3\, log_2\,(M)}{2(M-1)}$,$While\ erfc$ is the complementary error function. Then, the total BER of simultaneous worked QAM-OFDM/HSF-DC can be calculated as in the following:

$$BER_{Hybrid} = \frac{1}{2}(BER_{QAM-OFDM} + BER_{HSF-DC}) \tag{3.38}$$

3.6 SUMMERY

This work proposes Hermitian symmetry free approach based OFDM for VLC systems. The proposed scheme HSF-DC achieves100% enhancement of the spectrum efficiency of VLC system without sacrificing bandwidth, by exploiting the frame structure of PAM-OFDM. When using the proposed scheme in VLC system, the requirement of Hermitian symmetry property is alleviated, and the spectrum efficiency is improved compared with DC-biased and asymmetry clipping schemes. Moreover, the proposed HSF-DC based VLC system can achieve the same SE of DCO, PAM-DMT, and ACO but with lower modulation index and hence it can highly reduce the power requirements. Significant power gain is achieved when applying HSF-DC compared to PAM-DMT, while the average transmitted power is reduced by half compared with DCO.

A spectrally efficient hybrid RF/VLC network is also proposed in this chapter. In the proposed hybrid network, two efficient schemes are integrated to work simultaneously to support high data rate transmission. The first one is QAM-OFDM for WiFi sub-network and HSF-DC to perform the intensity modulation and direct detection at LiFi. Results show that for all the hybrid approaches, there are number of modulation order's modes can be combined by RF and VLC to achieve the required SE point for SE > 4 bps/Hz. Each modulation order mode has different BER performance compared with others achieving the same SE value. This possibility adds more flexibility to the hybrid systems to choose the best mode based on the best SNR. Theoretical derivatives show that the proposed hybrid QAM-OFDM/HSF-DC network improved the spectral efficiency with gain of (1.3) over hybrid QAM-OFDM/PAM-DMT and QAM-OFDM/DCO.

4. SIMULATION RESULTS

4.1. STAND-ALONE VLC SYSTEM BASED ON HSF-DC

4.1.1 Simulation Results and Discussion

The proposed scheme has undergone thorough simulation, which has been discussed and compared with the other optical OFDM methods. The performance of HSF-DC over an AWGN channel has been simulated using the parameters listed in Table 3.1.

In HSF-DC, different biasing levels are added to the bipolar signals to put it in unipolar form to test the performance. As a function of SNR within forward error correction (FEC) threshold @ 3.8e-3 for various spectral efficiency points, this section evaluates the BER performance of HSF-DC and PAM-DMT, DCO, and ACO for various modulation levels. 128 subcarriers are used for the simulations. The M constellation size of HSF-DC should be compared to M2-PAM-DMT, M2-DCO, and M4-ACO because SE of HSF-DC is 2 times that of PAM-DMT and DCO, and four times that of ACO, as shown in Figure 4.1. For example, 4-HSF-DC should be compared to 16-PAM-DMT,16-DCO and 256-ACO etc.

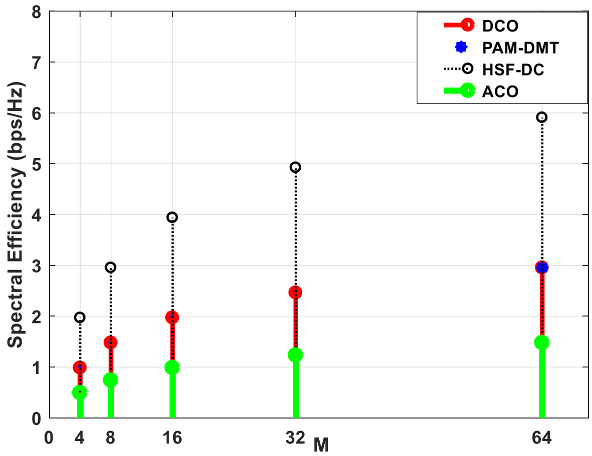

Figure 4.1: Spectral Efficiency HSF-DC, DCO,PAM-DMT, and ACO Versus Different Modulation Orders.

In agreement with other works [44] and to show how a moderate and large bias effect the performance of DC-biased schemes, Figures 4.2 and 4.3 use DC parameters of 7 dB and 13 dB, respectively. High bias boosts electrical power while lowering clipping noise. High DC levels have very little clipping noise, and a given BER requires an SNR equal to the SNR of a bipolar signal for high DC biasing. Figure 4.2 presents a comparison of the proposed HSF-DC and conventional DCO within biasing value of 7 dB. As it is shown, such DC value is efficient only for low modulation orders while for larger constellations the BER plots plateau as the clipping noise predominates. Additionally, it can be seen that at SE = 1 bps /Hz, the performance of 2-HSF-DC surpasses that of 4-DCO by 4 dB. Also, at SE = 2 bps /Hz, 4-HSF-DC saves also about 4 dB compared to 16-DCO.

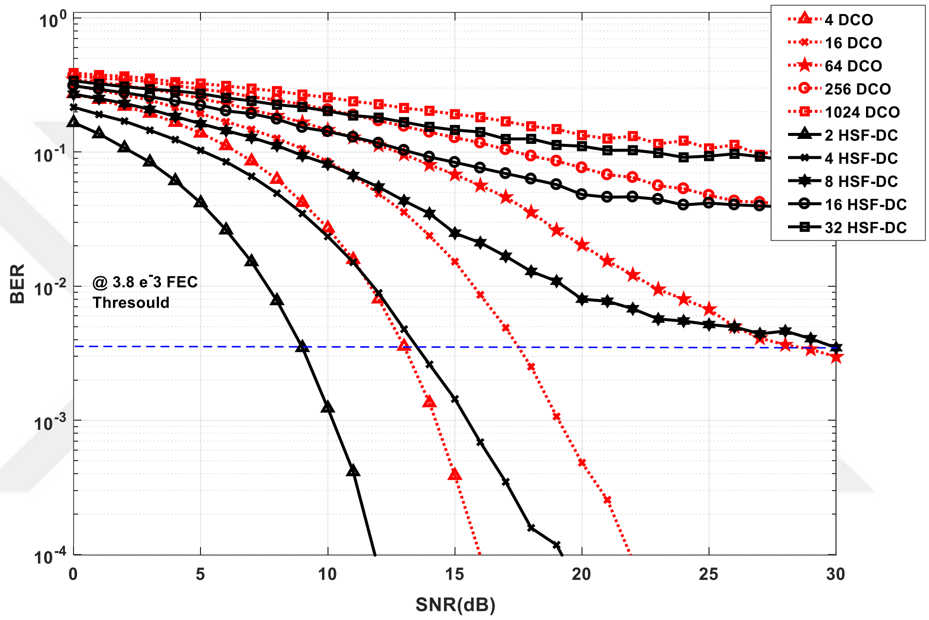

Figure 4.2: BER in AWGN Versus SNR for The Proposed HSF-DC and Conventional DCO With DC Bias of 7dB.

DC and conventional DCO. It can be seen that in all the presented cases, HSF-DC performance surpasses that of DCO by 10 dB for different spectral efficiency points. The constant power efficiency gain of HSD-DC over DCO can be clarified from the fact the transmitted power of HSF-DC is reduced by constant factor as shown in the derivatives of the past section and also adding the same DC bias value for both HSF-DC and DCO. For DC biased schemes, introducing less bias would result in more clipping and, consequently, greater BER value of the given SNR.

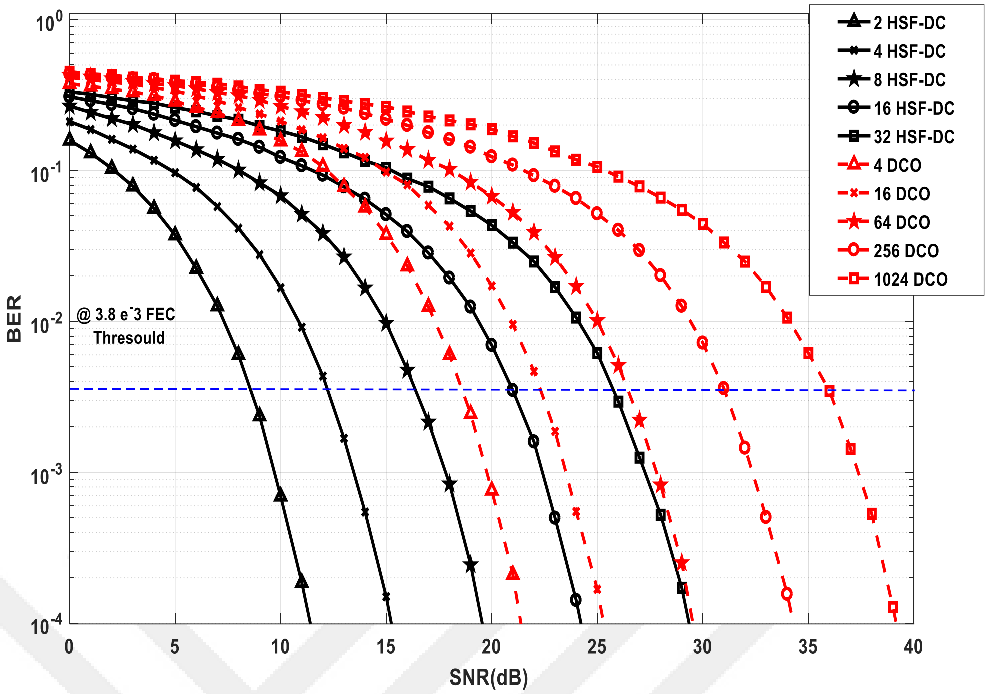

Figure 4.3: BER in AWGN Versus SNR for The Proposed HSF-DC and Conventional DCO With DC Bias of 13 dB.

Figure 4.4 shows the performance of HSF-DC, PAM-DMT, and ACO at BER of 10^{-4}. ACO shows a constant power gain of 1 dB over PAM-DMT. HSF-DCO requires a lower SNR than any other modulation schemes. At SE = 2 bps/Hz, 4-HSF-DC saves 8.5 dB and 9.5 dB over ACO and PAM-DMT respectively. Similarly, HSF-DC with 8-PAM requires 14.5 dB and 15.5 less power than 4096 ACO and 64-PAM-DMT.

In comparison with 256-PAM-DMT and 65536-ACO at SE = 4 bps/Hz, the energy efficiency improvement of 16-HSF-DC is 20.2 dB and 21.2 dB. Hence the proposed scheme with relatively very low modulation order is highly appreciated to achieve high SEs with high power efficiency.

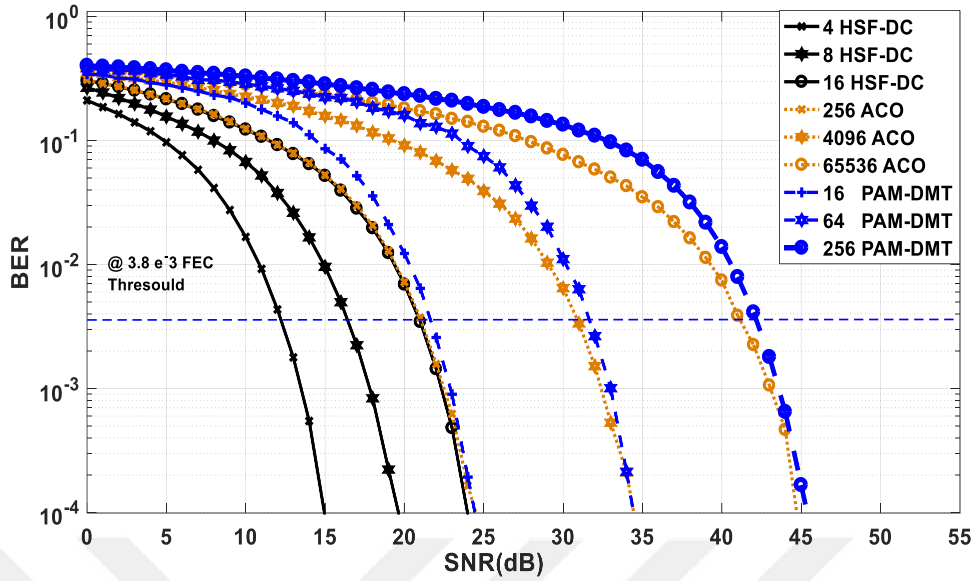

Figure 4.4: BER in AWGN Versus SNR for The Proposed HSF-DC With DC Bias of 13 dB, PAM-DMT and ACO.

As is well known, in order to meet certain BER criteria, higher order QAM requires higher SNR values.

Although large PAPR values in dc-biased schemes commonly lead to performance degradation for large K [19], such is not the case for our HSF-DC scheme because using a lower modulation order resulted in a reduction of PAPR, as shown by Figure 4.5.5. The complementary cumulative density function (CCDF) of PAPR, which is given by the expression of (PAPR>PAPR0), is calculated. It can be noted that non-DC biased schemes PAM-DMT and ACO achieved the same PAPR values at the same spectral efficiency points. Results are introduced for different spectral efficiency points. It is seen that at probability of 10^{-4}, 4-HSF-DC and 16-DCO has a reduced PAPR at 2.34 dB, while it is 3 dB for 16-non-DC biasing. At SE=3 bps/HZ, 8-HSF-DC reduces the PAPR by 0.6 dB and 8 dB compared to 64-DCO and 64-non-DC biasing schemes respectively. The reduction of PAPR becomes more significant for higher SE points. At SE=4 bps/Hz, 16-HSF-DC comes with PAPR reduction gain of 2.5 dB and more than 8 dB over 256-DCO and 256-non-DC biasing schemes respectively.

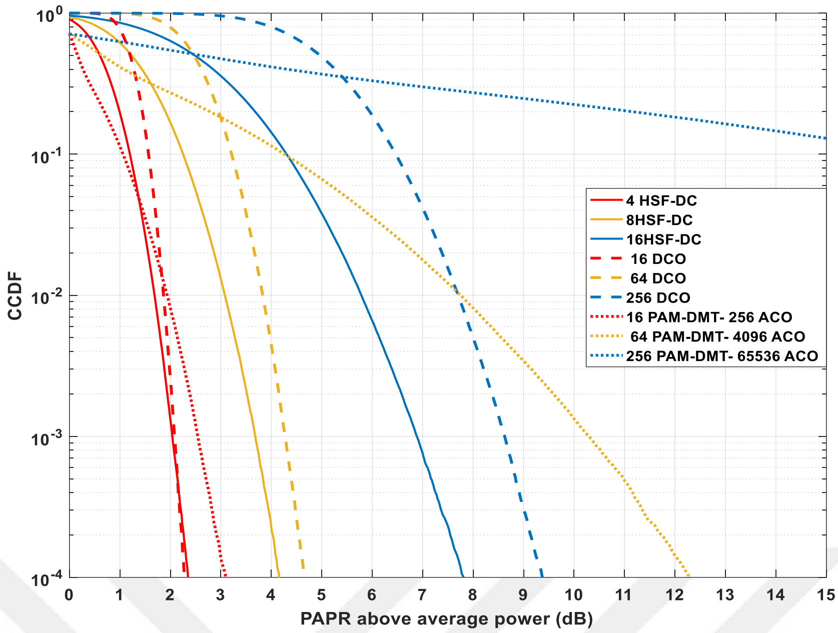

Figure 4.5: Complimentary Cumulative Distribution Function (CCDF) of The PAPR for The Proposed HSF-DC, DCO PAM-DMT, and ACO.

It is worth mentioning that the gain achieved by the proposed HSF-DC is due to avoiding Hermitian symmetry and using very low modulation orders compared to the others.

Figure 4.6 compares the performance of the suggested system for various modulation formats using a theoretical model and Monte Carlo simulations. We assume that the average of the unipolar signal is equal to the average of the bipolar signal. The plotted curves demonstrate that the presented model and the executed simulations have a good level of agreement.

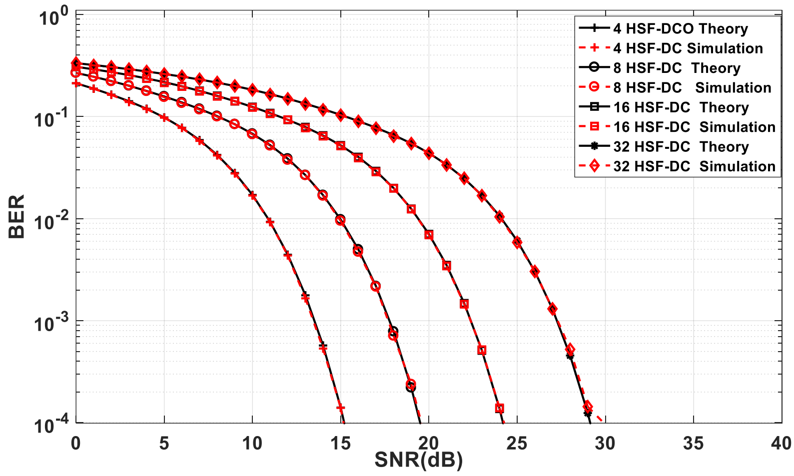

Figure 4.6: Theoretical HSF-DC Performance vs. Monte Carlo Simulations.

Basing on theoretical derivatives introduced and simulation results discussed in this section, Table 4.1 summarizes the comparative results of HSF-DC, DCO, PAM-DMT and ACO.

Table 4.1: Comparison of HSF-DC Over DCO, PAM-DMT, and ACO for Average Energy Per Bit (**E**) in joule / bit at $\boldsymbol{\varepsilon_g} = \mathbf{1}$.

SE	M_{HSF-DC}	E_{HSF-DC}	$M_{DCO\ or\ PAM-DMT}$	E_{DCO}	$E_{PAM-DMT}$ and E_{ACO}
1	2	0.25	4	0.5	1.25
2	4	0.625	16	1.25	10.625
3	8	1.75	64	3.5	113.75
4	16	5.3125	256	10.625	1365.3
5	32	17.5	1042	34.1	17476.25
6	64	56.875	4096	113.75	233016.875

It can be noted that $E_{PAM-DMT}$ and E_{ACO} are always equal to achieve the same SE since the average energy per bit E of M-PAM is equal to that of M^2-QAM and the spectral efficiency of PAM-DMT is twice than that of ACO. It can also be noted that HSF-DC requires always half the average energy per bit of DCO to achieve a spectral efficiency value because Hermitian symmetry free allow to use lower modulation order than DCO as shown in equation (3.17).

4.2 PERFORMANCE EVALUATION OF THE PROPOSED HYBRID QAM-OFDM/HSF-DC SYSTEM

This section demonstrates the BER performance of the QAM-OFDM/HSF-DC along with comparison with the relative hybrid RF/VLC systems based on DC-biased scheme as well as asymmetrically clipped scheme. Results are drawn at 10^{-4}. For the convenience of the reader, the channel and table 4.2 provides a summary of the simulation parameters. At the opposite of stand-alone networks, hybrid networks can employ different modes of modulation orders to achieve a spectral efficiency point as illustrated in Table 3.2. Each modulation mode consists of two modulation orders the first one corresponding to the RF sub-system and the second one is of VLC sub-system. Figure 4.7 shows that hybrid QAM-OFDM/HSF-DC can achieve 5 bps/HZ by two modulation orders modes (8,4) and (4,8). By the first mode, QAM-OFDM/HSF-DC achieves the best performance since QAM-OFDM sub-network is used to carry more data rate than HSF-DC sub-network. Figures 4.8, 4.9 and 4.10 clearly show that for each modulation orders' mode wherein $M_{QAM} > M_{VLC}$, QAM-OFDM/HSF-DC can achieve superior BER performance in comparison to QAM-OFDM. It is interesting to note that higher improvements are achieved for higher SE points.

Table 4.2: Simulation Parameters.

System Parameters	Values
System	OFDM
Channel type	AWGN
Tx and Rx Antenna	SISO
FFT/IFFT Points	128
Cyclic Prefix length	25%
Downlink	WiFi and LiFi simultaneously
DC-biasing	13dB
RF modulation technique	QAM

Figures 4.11, 4.12, 4.13 and 4.14 present comparisons of the BER performance for the proposed QAM-OFDM/HSF-DC with QAM-OFDM, QAM-OFDM/PAM-DMT, QAM-OFDM/DCO.

The energy gain of QAM-OFDM/HSF-DC over QAM-OFDM starts at 0.5 dB at SE = 5 dB and raised to 2 dB at SE = 6 bps/Hz. At higher spectral efficiencies 7 and 8 pbs/Hz, it is clear that the gain of proposed QAM-OFDM/HSF-DC reaches to 5 dB over RF system. In comparison with QAM-OFDM/PAM-DMT and QAM-OFDM/DCO, the proposed QAM-OFDM/HSF-DC saves 9.7 and 10.3 dB respectively at both SE = 5 and 6 bps/Hz. At highest spectral efficiency 8 bps/Hz, the gain is reduced to 7.7 dB over QAM-OFDM/PAM-DMT and 9.3 dB over QAM-OFDM/DCO.

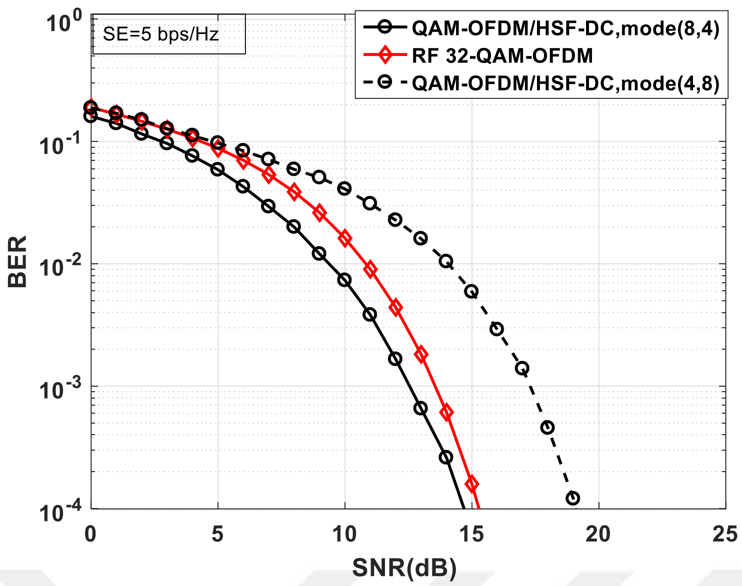

Figure 4.7: BER Performance of Hybrid QAM-OFDM/HSF-DC Vs Stand-Alone RF System Based on QAM-OFDM**.**

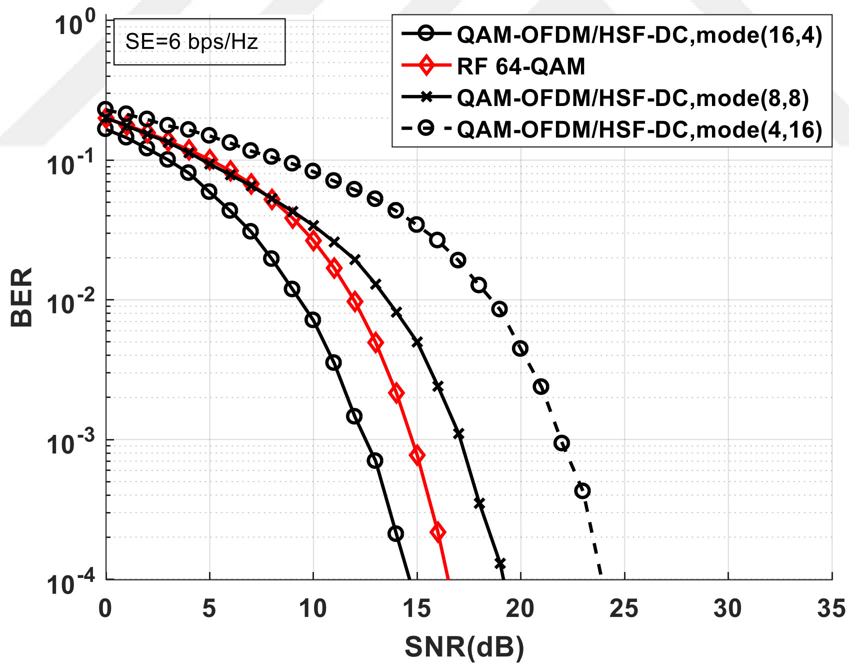

Figure 4.8: BER Performance of Hybrid QAM-OFDM/HSF-DC Vs Stand-Alone RF System Based on QAM-OFDM.

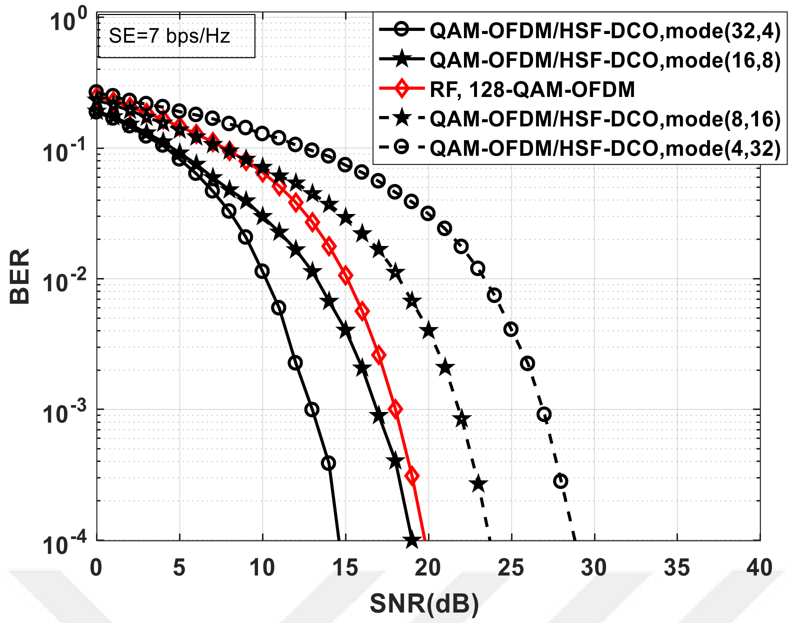

Figure 4.9: BER Performance of Hybrid QAM-OFDM/HSF-DC Vs Stand-Alone RF System Based on QAM-OFDM.

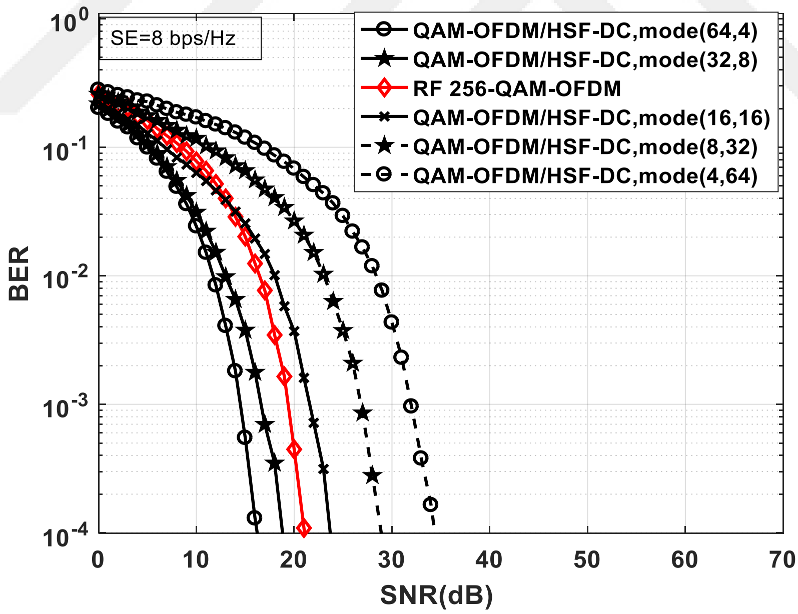

Figure 4.10: BER Performance of Hybrid QAM-OFDM/HSF-DC Vs Stand-Alone RF System Based on QAM-OFDM.

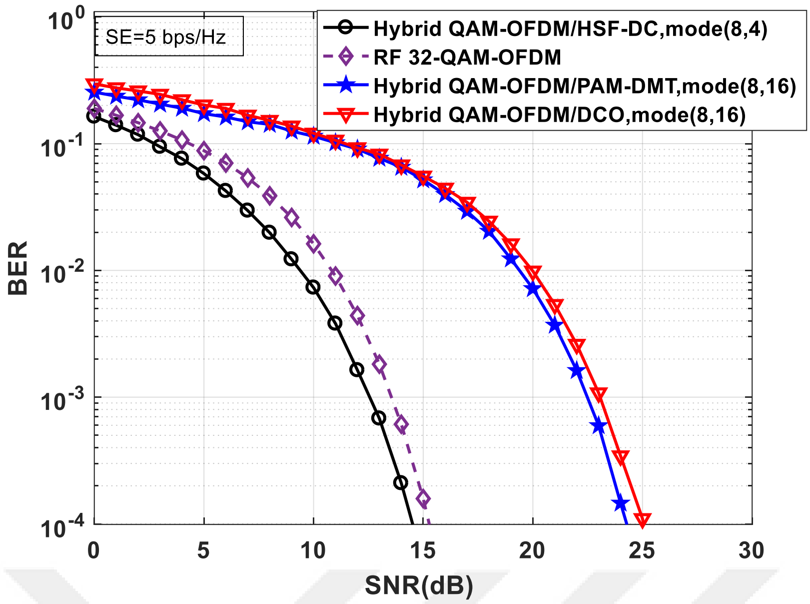

Figure 4.11: BER Performance of Hybrid QAM-OFDM/HSF-DC Vs Stand-Alone RF System Based on QAM-OFDM and Hybrid QAM-OFDM/PAM-DMT QAM-OFDM/DCO.

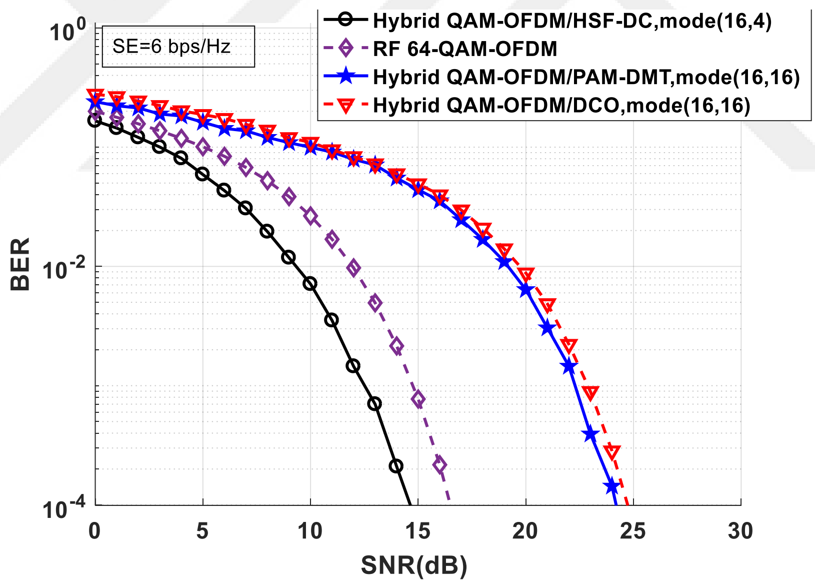

Figure 4.12: BER Performance of Hybrid QAM-OFDM/HSF-DC Vs Stand-Alone RF System Based on QAM-OFDM and Hybrid QAM-OFDM/PAM-DMT QAM-OFDM/DCO.

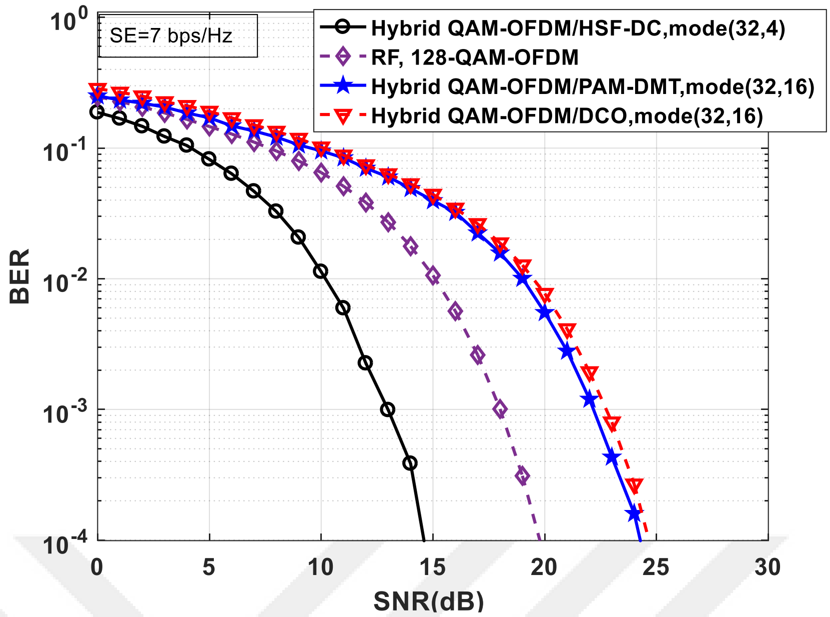

Figure 4.13: BER Performance of Hybrid QAM-OFDM/HSF-DC Vs Stand-Alone RF System Based on QAM-OFDM and Hybrid QAM-OFDM/PAM-DMT QAM-OFDM/DCO.

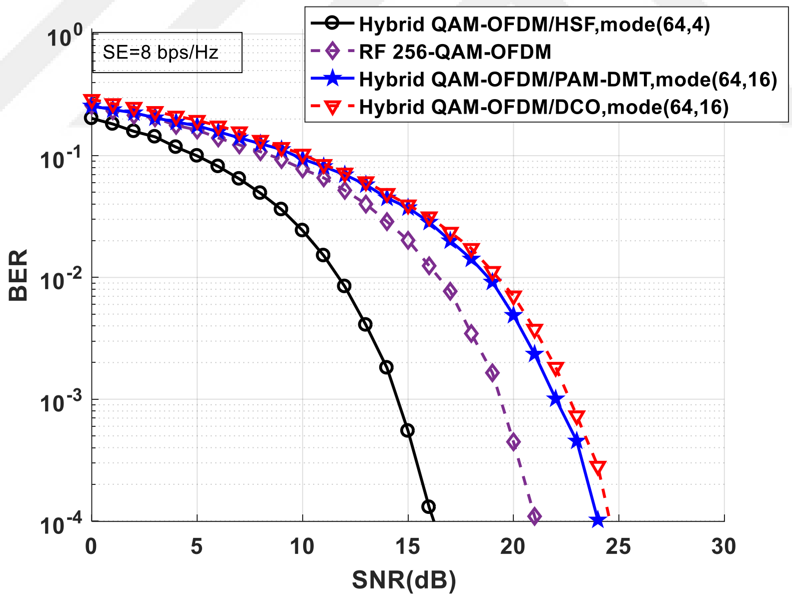

Figure 4.14: BER Performance of Hybrid QAM-OFDM/HSF-DC Vs Stand-Alone RF System Based on QAM-OFDM and Hybrid QAM-OFDM/PAM-DMT QAM-OFDM/DCO.

Figure 4.15 summarizes all the comparisons. Since, HSF-DC has the best BER compared with DCO and PAMT. IT is expected that the proposed QAM-OFDM/HSF-DC outperform QAM-OFDM/DCO and QAM-OFDM/PAM-DMT. Typically, QAM has better BER performance over PAM, however, QAM-OFDM/DCO with 13 dB bias requires the highest SNR values. It is evident that the performance of QAM-OFDM/DCO and QAM-OFDM/PAM-DMT is slightly changed while increasing the spectral efficiency. It is also clear that the energy efficiency of hybrid QAM-OFDM/PAM-DMT is better than that of QAM-OFDM/DCO with gain of 0.6 dB.

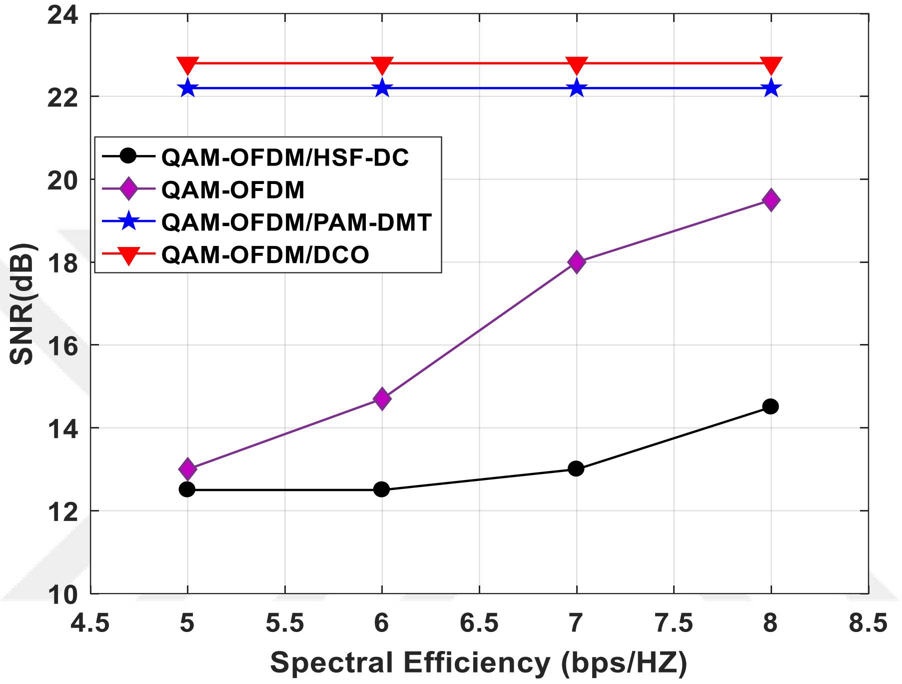

Figure 4.15: Spectral Efficiency Vs. Required SNR, at BER =$\mathbf{10^{-3}}$.

The Monte-Carlo simulations are used to validate the analytical BER expression. as presented in Figure 4.16. The plotted curves show that the presented model is identical to the conducted simulations.

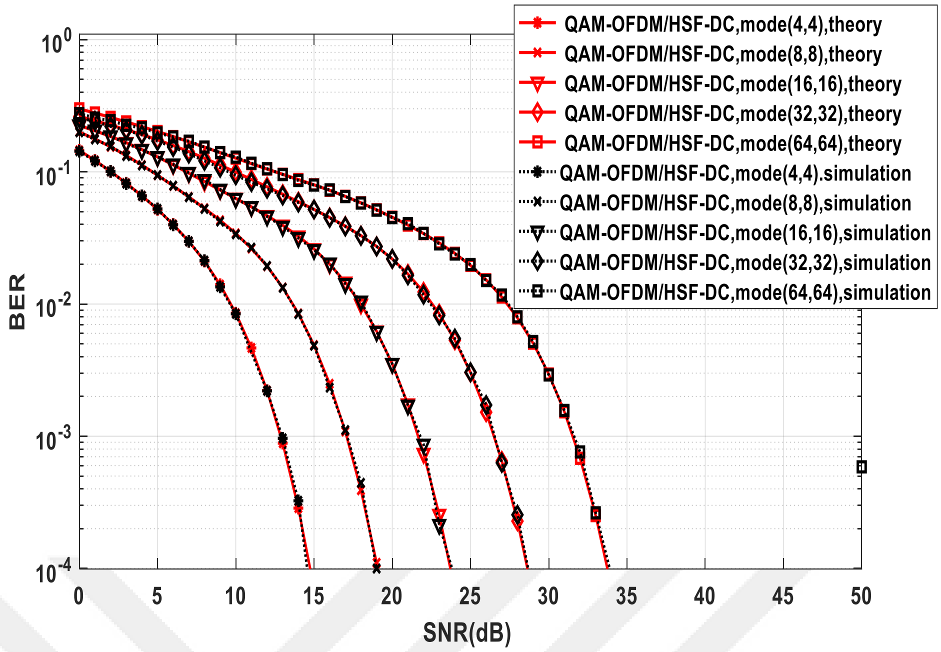

Figure 4.16: Theoretical BER Performance Vs. Simulation.

4.3 SUMMERY

Due to the increasing global demand for high-speed data access, wireless communication facing many challenges especially in terms of capacity, availability, security, power and spectral efficiencies. For indoor high data rate wireless communication, one auspicious way is to coordinate wireless fidelity (WiFi) with light fidelity (LiFi), to produce hybrid LiFi and WiFi networks (HWLNs). These hybrid networks combine the high-speed connection of LiFi and the ubiquitous coverage of WiFi. To perform WiFi technology, QAM is the most dominate modulation approach suitable to be applied due to its efficiency. From other hand, VLC systems apply simple and cheap IM/DD techniques. For IM/DD, the transmitted signal is required to be real and positive due to conditions. Hermitian symmetry is applied to satisfy real signals. However, this operation reduces the spectral efficiency of VLC systems by half compared with RF systems. Based on clipping and rearranging idea, we propose enhanced scheme to be applied for IM/DD called Hermitian symmetry free with direct current biasing. The proposed scheme does not apply Hermitian symmetry process to transform the complex signal to real form. Instead, the proposed scheme applies clipping and rearrangement operations to guarantee the signal to be in the real form. Then a suitable DC-biasing is added to the real signal in order to get unipolar form. The enhanced approach used PAM-OFDM in modified way to increase the spectral efficiency twice compared to conventional IM/DD schemes.

Simulation results confirm that the HSF-DC outperforms DCO, PAM-DMT and ACO schemes in terms of BER performance under same spectral efficiency. This enhancement is achieved due to two reasons. The first one is that the modulation order required by HSF-DC is equal to the square root of the modulation order of DCO and PAM-DMT, while it is the fourth root of the constellations size applied by ACO.

The second reason is that avoiding to apply Hermitian symmetry resulted in reducing the PAPR which in turns minimizing the effect of the clipping noise and enhancing the BER. The improvements of BER become more interesting while increasing the SE points because the BER performance deteriorates more and more for higher M of DCO, ACO and PAM-DMT.

Interesting results are noted while increasing the SE, e.g., at SE= 4 bps/Hz, the energy efficiency improvement of 16-HSF-DC is 10, 20.2, 21.2 dB compared with 256-DCO, 256-PAM-DMT and 65536-ACO respectively. Furthermore, at spectral efficiency of 3 bps/Hz and CCDF of 10^{-4}, a PAPR gain of 9.5 dB over PAM-DMT and ACO, while it is 0.9 over DCO. In addition, at SE= 5 bps/Hz. HSF-DC has a PAPR gain of more than 10 dB compared with PAM-DMT and ACO and 3 dB over DCO. As a result, our suggested method is a good competitor and has the potential to be applied to applications requiring high-speed VLC systems.

When the spectrally efficient VLC based on HSF-DC is integrated with QAM-OFDM a spectrally efficient hybrid network is built. For hybrid communication networks, it is possible to achieve a spectral efficiency point by different modulation orders modes. This advantage makes it possible for the proposed QAM-OFDM/ HSF-DC to achieve better BER performance compared to QAM-OFDM when the applied M-sub-VLC < M-sub-RF. This is because VLC systems requires higher SNR compared with RF system to achieve a reduced BER.

For fair comparison we compare 4-HSF-DC sub system with 16-DCO, 16-PAM-DMT as it is the lowest order can be applied by VLC sub system to achieve 2 bps/HZ. At SE = 8 bps/Hz, 64-QAM-OFDM is merged with 4-HSF-DC but with 16-DCO, 16-PAM-DMT. Since the BER curve gap between (16-DCO, 16-PAM-DMT) and (8,16,23, 64-QAM-OFDM) is high, higher SNR values are required for QAM-OFDM/DCO and DCO, QAM-OFDM/PAM-DMT compared with QAM-OFDM/HSF-DC.

5. CONCLUSIONS AND FUTURE WORKS

5.1 CONCLUSIONS

This work addresses the development and implementation of hybrid WiFi and LiFi networks (HWLNs) based on OFDM scheme. The research considers the problem of modelling the OFDM based HWLNs system covering the spectral efficiency assessment and transmitted energy efficiency improvements as well as BER performance enhancements. The proposed model shall serve as the guidance for future wireless communication system and to be a part of the overall wireless communication solution and all the outlined objectives have been successfully achieved. The main conclusions of this thesis are summarized as follow:

First, A new, more effective method of transmitting optical OFDM signals without using Hermitian symmetry has been introduced. In order to achieve twofold spectral efficiency with acceptable BER performance in VLC systems, the proposed HSF-DC scheme achieves the real signal representation without Hermitian symmetry. The suggested HSF-DC scheme then produces the unipolar signals by including a DC-bias, similar to how DCO-OFDM does it. In terms of spectral efficiency, transmitted energy, BER enhancements, and PAPR reduction, the proposed scheme has been compared with other DC-biased schemes and asymmetrically clipped schemes. The advantages of the proposed scheme include a two-fold increase in spectral efficiency over comparable schemes like DCO and PAM-DMT schemes. Additionally, for all spectral efficiency values, the recommended HSF-DC based VLC system has the best BER performance. Additionally, it is observed that the HSF-DC scheme consumes less transmitted energy because it can efficiently achieve a same SE with a smaller constellation size. Compared with PAM-DMT and ACO, the proposed HSF-DC saves 80% at SE = 1 bps/HZ and reaches to 99% at SE > 3 bps/HZ. In addition, the energy saving factor of HSF-DC over DCO is 50 % for all SE points. Results also showed that HSF-DC has the best PAPR performance compared to its counterparts.

Furthermore, in this work, HSF-DC has been integrated with RF system to build a spectrally efficient hybrid network called QAM-OFDM/HSF-DC. The performance analysis of QAM-OFDM/HSF-DC network is investigated in terms of BER and spectral efficiency with the effect of modulation order. As it is expected, when compared to QAM-OFDM/DCO and

QAM-OFDM/PAM-DMT the proposed QAM-OFDM/HSF-DC network significantly improves the spectral efficiency with a gain of 1.3. Results show that for all the hybrid wireless networks, there are number of modulation order's modes can be combined by RF and VLC networks to achieve the required SE point when SE > 4 bps/Hz. Each modulation orders mode collection has different BER performance compared with others for the same SE value. The BER performance of QAM-OFDM/HSF-DC network has been compared with related hybrid communication networks such as QAM-OFDM/DCO and QAM-OFDM/PAM-DMT. For all the studied cases, much lower SNR for QAM-OFDM/HSF-DC is required to achieve the BER target shows that the suggested scheme has a high-power efficiency.

5.2 FUTURE WORKS

A great deal of effort has been devoted to making this work perfect in every way. There are many possibilities that can be researched further. If this scheme can be putted into practical application, wireless VLC networks can transmit double data rate. The proposed scheme applies clipping and reshaping operations on the time domain signal to make it real instead of Hermitian symmetry to improve SE, EE, BER, and PAPR. In addition, there is an endless road of possible improvements to the SE and BER of RF/VLC systems. The study presented in this thesis has concerned on the assessment and improvement of the hybrid RF/VLC's SE and BER using clipping, rearrangement operations. Future studies can also include the channel estimation techniques for further improvement of the scheme proposed in this dissertation. For further research, the following ideas could be tested:

a. A behavioral model for a hardware description language (HDL) simulation, insights into the analysis and visualization capabilities for real-time into an HDL implementation.

b. Study the performance of QAM-OFDM/HSF-DC under outdoor environment and multipath fading channel.
c. Applying MIMO technology with HSF-DC approach for spatial modulation and study the possible enhancements.
d. Using this hybrid approach along with nonorthogonal division multiple access (NOMA).

REFERENCES

[1] M. Asad and S. Qaisar, “Energy Efficient QoS-Based Access Point Selection in Hybrid WiFi and LiFi IoT Networks,” *IEEE Trans. Green Commun. Netw.*, vol. 6, no. 2, pp. 897–906, 2022, doi: 10.1109/TGCN.2021.3115729.

[2] X. Wu, M. D. Soltani, L. Zhou, M. Safari, and H. Haas, “Hybrid LiFi and WiFi Networks: A Survey,” *IEEE Commun. Surv. Tutorials*, vol. 23, no. 2, pp. 1398–1420, 2021, doi: 10.1109/COMST.2021.3058296.

[3] D. Tsonev and H. Haas, “Avoiding spectral efficiency loss in unipolar OFDM for optical wireless communication,” *2014 IEEE Int. Conf. Commun. ICC 2014*, pp. 3336–3341, 2014, doi: 10.1109/ICC.2014.6883836.

[4] Z. Zeng, M. Dehghani Soltani, Y. Wang, X. Wu, and H. Haas, “Realistic Indoor Hybrid WiFi and OFDMA-Based LiFi Networks,” *IEEE Trans. Commun.*, vol. 68, no. 5, pp. 2978–2991, 2020, doi: 10.1109/TCOMM.2020.2974458.

[5] A. Gupta, P. Garg, and N. Sharma, “Hybrid LiFi - WiFi Indoor Broadcasting System,” *IEEE Int. Symp. Pers. Indoor Mob. Radio Commun. PIMRC*, vol. 2017-Octob, pp. 1–6, 2018, doi: 10.1109/PIMRC.2017.8292476.

[6] M. B. Rahaim, A. M. Vegni, and T. D. C. Little, “A hybrid Radio Frequency and broadcast Visible Light Communication system,” *2011 IEEE GLOBECOM Work. GC Wkshps 2011*, pp. 792–796, 2011, doi: 10.1109/GLOCOMW.2011.6162563.

[7] I. Stefan and H. Haas, “Hybrid visible light and radio frequency communication systems,” in *2014 IEEE 80th Vehicular Technology Conference (VTC2014-Fall)*, 2014, pp. 1–5.

[8] S. Singh, A. Verma, S. Chatterjee, and V. Ramana, “An Efficient methodology to solve the K-terminal network reliability problem,” *2016 3rd Int. Conf. Recent Adv. Inf. Technol. RAIT 2016*, pp. 25–28, 2016, doi: 10.1109/RAIT.2016.7507869.

[9] M. Ayyash *et al.*, “Coexistence of WiFi and LiFi toward 5G: concepts, opportunities, and challenges,” *IEEE Commun. Mag.*, vol. 54, no. 2, pp. 64–71, 2016.

[10] A. Khreishah, S. Shao, A. Gharaibeh, M. Ayyash, H. Elgala, and N. Ansari, “A hybrid RF-VLC system for energy efficient wireless access,” *IEEE Trans. Green Commun. Netw.*, vol. 2, no. 4, pp. 932–944, 2018.

[11] M. Obeed, A. M. Salhab, M.-S. Alouini, and S. A. Zummo, "On optimizing VLC networks for downlink multi-user transmission: A survey," *IEEE Commun. Surv. \& Tutorials*, vol. 21, no. 3, pp. 2947–2976, 2019.

[12] D. Tsonev, S. Sinanovic, and H. Haas, "Novel unipolar orthogonal frequency division multiplexing (U-OFDM) for optical wireless," *IEEE Veh. Technol. Conf.*, 2012, doi: 10.1109/VETECS.2012.6240060.

[13] Y. Wang and H. Haas, "Dynamic Load Balancing with Handover in Hybrid Li-Fi and Wi-Fi Networks," *J. Light. Technol.*, vol. 33, no. 22, pp. 4671–4682, 2015, doi: 10.1109/JLT.2015.2480969.

[14] S. Ullah, S. U. Rehman, and P. H. J. Chong, "A comprehensive open-source simulation framework for lifi communication," *Sensors*, vol. 21, no. 7, pp. 1–22, 2021, doi: 10.3390/s21072485.

[15] F. B. Ogunkoya, W. O. Popoola, and S. Sinanovic, "PAPR reduction in optical OFDM with grouped LEDs," *2016 10th Int. Symp. Commun. Syst. Networks Digit. Signal Process. CSNDSP 2016*, 2016, doi: 10.1109/CSNDSP.2016.7573925.

[16] S. D. Dissanayake and J. Armstrong, "Comparison of aco-ofdm, dco-ofdm and ado-ofdm in im/dd systems," *J. Light. Technol.*, vol. 31, no. 7, pp. 1063–1072, 2013.

[17] O. Ugweje, "Radio Frequency and Wireless Communications Security," 2004.

[18] J. G. Proakis, *Fifth Edition*.

[19] J. Li, X. Da Zhang, Q. Gao, Y. Luo, and D. Gu, "Exact BEP analysis for coherent M-ary PAM and QAM over AWGN and Rayleigh fading channels," *IEEE Veh. Technol. Conf.*, no. June, pp. 390–394, 2008, doi: 10.1109/VETECS.2008.93.

[20] S. Gupta and H. Sharma, "Performance Investigation for different modulation techniques in WCDMA with multipath fading channels," *Int. J. Adv. Res. Comput. Sci. Softw. Eng.*, vol. 2, no. 7, pp. 20–23, 2012.

[21] C. Ndujiuba, O. OMOTAYO Oni, A. Ehiremen Ibhaze, C. U. Ndujiuba, O. Oni, and A. E. Ibhaze, "Comparative Analysis of Digital Modulation Techniques in LTE 4G Systems," *Artic. J. Wirel. Netw. Commun.*, vol. 5, no. 2, pp. 60–66, 2015, doi: 10.5923/j.jwnc.20150502.02.

[22] M. Trikha, N. Sharma, M. Singhal, R. Rajan, and P. Bhardwaj, "BER performance comparison between QPSK and 4-QA modulation schemes," *MIT Int. J. Electr. Instrum. Eng.*, vol. 3, no. 2, pp. 62–66, 2013.

[23] M. Barnela and D. S. Kumar, “Digital modulation schemes employed in wireless communication: A literature review,” *Int. J. Wired Wirel. Commun.*, vol. 2, no. 2, pp. 15–21, 2014.

[24] J. Lee, H. L. Lou, D. Toumpakaris, and J. M. Cioffi, “SNR analysis of OFDM systems in the presence of carrier frequency offset for fading channels,” *IEEE Trans. Wirel. Commun.*, vol. 5, no. 12, pp. 3360–3364, 2006, doi: 10.1109/TWC.2006.256956.

[25] A. B. Singh and K. G. Vivek, “A Review Paper on Channel Estimation Techniques Used in OFDM System,” *Int. J. Eng. Trends Technol.*, pp. 226–229, 2014.

[26] D. W. Bliss, K. W. Forsythe, and A. M. Chan, “MIMO wireless communication,” 2005.

[27] R. C. Meitzler, W. Schneider, and R. Conde, “IRCOMM: spacecraft free-space optical bus development,” in *2005 IEEE Aerospace Conference*, 2005, pp. 1583–1588.

[28] L. Hanzo, H. Haas, S. Imre, D. O’Brien, M. Rupp, and L. Gyongyosi, “Wireless myths, realities, and futures: from 3G/4G to optical and quantum wireless,” *Proc. IEEE*, vol. 100, no. Special Centennial Issue, pp. 1853–1888, 2012.

[29] A. A. Abdulkafi, S. M. Hardan, O. Bayat, and O. N. Ucan, “Multilayered optical OFDM for high spectral efficiency in visible light communication system,” *Photonic Netw. Commun.*, vol. 38, no. 3, pp. 299–313, 2019.

[30] Y. Tanaka, T. Komine, S. Haruyama, and M. Nakagawa, “Indoor visible communication utilizing plural white LEDs as lighting,” in *12th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications. PIMRC 2001. Proceedings (Cat. No. 01TH8598)*, 2001, vol. 2, p. F--F.

[31] H. Elgala, R. Mesleh, and H. Haas, “Indoor broadcasting via white LEDs and OFDM,” *IEEE Trans. Consum. Electron.*, vol. 55, no. 3, pp. 1127–1134, 2009.

[32] A. Yesilkaya, E. Basar, F. Miramirkhani, E. Panayirci, M. Uysal, and H. Haas, “Optical MIMO-OFDM with generalized LED index modulation,” *IEEE Trans. Commun.*, vol. 65, no. 8, pp. 3429–3441, 2017.

[33] O. Anilkumar and R. K. Jeyachitra, “Performance enhancement of indoor VLC system by employing SAC OCDMA technique,” *Proc. 2017 Int. Conf. Wirel. Commun. Signal Process. Networking, WiSPNET 2017*, vol. 2018-Janua, pp. 1784–1789, 2018, doi: 10.1109/WiSPNET.2017.8300068.

[34] J. Grubor, S. Randel, K.-D. Langer, and J. W. Walewski, “Bandwidth-efficient indoor optical wireless communications with white light-emitting diodes,” in *2008 6th International Symposium on Communication Systems, Networks and Digital Signal Processing*, 2008, pp. 165–169.

[35] D. O’Brien *et al.*, “Indoor visible light communications: challenges and prospects,” *Free. Laser Commun. VIII*, vol. 7091, pp. 60–68, 2008.

[36] S. Hranilovic, *Wireless optical communication systems*. Springer Science \& Business Media, 2006.

[37] T. Komine and M. Nakagawa, “Fundamental analysis for visible-light communication system using LED lights,” *IEEE Trans. Consum. Electron.*, vol. 50, no. 1, pp. 100–107, 2004.

[38] J. M. Kahn and J. R. Barry, “Wireless infrared communications,” *Proc. IEEE*, vol. 85, no. 2, pp. 265–298, 1997.

[39] G. W. Marsh and J. M. Kahn, “Performance evaluation of experimental 50-Mb/s diffuse infrared wireless link using on-off keying with decision-feedback equalization,” *IEEE Trans. Commun.*, vol. 44, no. 11, pp. 1496–1504, 1996.

[40] Z. Yu, R. J. Baxley, and G. T. Zhou, “Brightness control in dynamic range constrained visible light OFDM systems,” in *2014 23rd Wireless and Optical Communication Conference (WOCC)*, 2014, pp. 1–5.

[41] W. O. Popoola, E. Poves, and H. Haas, “Error performance of generalised space shift keying for indoor visible light communications,” *IEEE Trans. Commun.*, vol. 61, no. 5, pp. 1968–1976, 2013.

[42] W. Hong, T. Li, W. Li, and X. Shi, “Analysis of DCO-OFDM for Indoor Visible Light Communications,” *J. Phys. Conf. Ser.*, vol. 1606, no. 1, 2020, doi: 10.1088/1742-6596/1606/1/012005.

[43] S. D. Dissanayake, S. Member, J. Armstrong, and S. Member, “Comparison of ACO-OFDM , DCO-OFDM and ADO-OFDM in IM / DD Systems,” vol. 31, no. 7, pp. 1063–1073, 2013.

[44] J. Armstrong and B. J. C. Schmidt, “Comparison of asymmetrically clipped optical OFDM and DC-biased optical OFDM in AWGN,” *IEEE Commun. Lett.*, vol. 12, no. 5, pp. 343–345, 2008, doi: 10.1109/LCOMM.2008.080193.

[45] S. C. J. Lee, S. Randel, F. Breyer, and A. M. J. Koonen, “PAM-DMT for intensity-modulated and direct-detection optical communication systems,” *IEEE Photonics Technol. Lett.*, vol. 21, no. 23, pp. 1749–1751, 2009.

[46] K. Vejandla, S. Kollikonda, and V. M. Vakamulla, “Performance Analysis of PAM-DMT under Double sided Signal Clipping in IM/DD Based Systems,” *26th Natl. Conf. Commun. NCC 2020*, 2020, doi: 10.1109/NCC48643.2020.9056086.

[47] S. Dimitrov, S. Sinanovic, and H. Haas, “Clipping noise in OFDM-based optical wireless communication systems,” *IEEE Trans. Commun.*, vol. 60, no. 4, pp. 1072–1081, 2012.

[48] M. B. Rahaim, A. M. Vegni, and T. D. C. Little, “A hybrid radio frequency and broadcast visible light communication system,” in *2011 IEEE GLOBECOM Workshops (GC Wkshps)*, 2011, pp. 792–796.

[49] S. Shao *et al.*, “An indoor hybrid WiFi-VLC internet access system,” in *2014 IEEE 11th International Conference on Mobile Ad Hoc and Sensor Systems*, 2014, pp. 569–574.

[50] Z. Zeng, M. D. Soltani, Y. Wang, X. Wu, and H. Haas, “Realistic indoor hybrid WiFi and OFDMA-based LiFi networks,” *IEEE Trans. Commun.*, vol. 68, no. 5, pp. 2978–2991, 2020.

[51] A. M. Abdelhady, O. Amin, A. Chaaban, B. Shihada, and M.-S. Alouini, “Spectral-efficiency—Illumination Pareto front for energy harvesting enabled VLC systems,” *IEEE Trans. Commun.*, vol. 67, no. 12, pp. 8557–8572, 2019.

[52] C. Chen, D. A. Basnayaka, and H. Haas, “Downlink performance of optical attocell networks,” *J. Light. Technol.*, vol. 34, no. 1, pp. 137–156, 2015.

[53] S. Pergoloni, M. Biagi, S. Colonnese, R. Cusani, and G. Scarano, “Optimized LEDs footprinting for indoor visible light communication networks,” *IEEE Photonics Technol. Lett.*, vol. 28, no. 4, pp. 532–535, 2015.

[54] M. Ayyash *et al.*, “Coexistence of WiFi and LiFi Toward 5G : Concepts , Opportunities , and Challenges,” no. February, pp. 64–71, 2016.

[55] P. A. Haigh *et al.*, “A multi-CAP visible-light communications system with 4.85-b/s/Hz spectral efficiency,” *IEEE J. Sel. Areas Commun.*, vol. 33, no. 9, pp. 1771–1779, 2015.

[56] T. Wang, F. Yang, L. Cheng, and J. Song, “Generalized spatial modulation based hybrid dimming scheme for visible light communication,” in *2018 IEEE Global Communications Conference (GLOBECOM)*, 2018, pp. 1–6.

[57] R. Bian, I. Tavakkolnia, and H. Haas, “15.73 Gb/s visible light communication with off-the-shelf LEDs,” *J. Light. Technol.*, vol. 37, no. 10, pp. 2418–2424, 2019.

[58] D. A. Basnayaka and H. Haas, “Hybrid RF and VLC systems: Improving user data rate performance of VLC systems,” in *2015 IEEE 81st vehicular technology conference (VTC Spring)*, 2015, pp. 1–5.

[59] Y. Sun, F. Yang, and L. Cheng, “An overview of OFDM-based visible light communication systems from the perspective of energy efficiency versus spectral efficiency,” *Ieee Access*, vol. 6, pp. 60824–60833, 2018.

[60] M. Kashef, M. Ismail, M. Abdallah, K. A. Qaraqe, and E. Serpedin, “Energy efficient resource allocation for mixed RF/VLC heterogeneous wireless networks,” *IEEE J. Sel. Areas Commun.*, vol. 34, no. 4, pp. 883–893, 2016.

[61] Y. Wang, X. Wu, and H. Haas, “Analysis of area data rate with shadowing effects in Li-Fi and RF hybrid network,” in *2016 IEEE international conference on communications (ICC)*, 2016, pp. 1–5.

[62] T. H. Loh *et al.*, “Link performance evaluation of 5G mm-wave and LiFi systems for the transmission of holographic 3D display data,” in *2019 13th European Conference on Antennas and Propagation (EuCAP)*, 2019, pp. 1–4.

[63] D. Konings, B. Parr, C. Waddell, F. Alam, K. M. Arif, and E. M. K. Lai, “HVLP: Hybrid visible light positioning of a mobile robot,” in *2017 24th International Conference on Mechatronics and Machine Vision in Practice (M2VIP)*, 2017, pp. 1–6.

[64] T. S. Rappaport and others, *Wireless communications: principles and practice*, vol. 2. prentice hall PTR New Jersey, 1996.

[65] J. G. Proakis and M. Salehi, *Essentials of communication systems engineering*. Prentice Hall, 2005.

[66] C. Zeyu, “6G, LIFI and WIFI Wireless Systems: Challenges, Development and Prospects,” *2021 18th Int. Comput. Conf. Wavelet Act. Media Technol. Inf. Process. ICCWAMTIP 2021*, pp. 322–325, 2021, doi: 10.1109/ICCWAMTIP53232.2021.9674090.

[67] Y. Tang, M. Brandt-Pearce, and S. G. Wilson, “Link adaptation for throughput optimization of parallel channels with application to hybrid FSO/RF systems,” *IEEE Trans. Commun.*, vol. 60, no. 9, pp. 2723–2732, 2012.

[68] O. Awwad, A. Al-Fuqaha, B. Khan, and G. Ben Brahim, “Topology control schema for better QoS in hybrid RF/FSO mesh networks,” *IEEE Trans. Commun.*, vol. 60, no. 5, pp. 1398–1406, 2012, doi: 10.1109/TCOMM.2012.12.110069.

[69] H. Samimi and M. Uysal, “End-to-end performance of mixed RF/FSO transmission systems,” *J. Opt. Commun. Netw.*, vol. 5, no. 11, pp. 1139–1144, 2013.

[70] N. I. Miridakis, M. Matthaiou, and G. K. Karagiannidis, “Multiuser relaying over mixed RF/FSO links,” *IEEE Trans. Commun.*, vol. 62, no. 5, pp. 1634–1645, 2014.

[71] B. Sukanya and V. Palliyembil, “Performance Improvement of Indoor Lifi Mobile Users with Random Orientation Using Hybrid Lifi and Wifi Networks (HLWNets),” *2021 Int. Conf. Wirel. Commun. Signal Process. Networking, WiSPNET 2021*, pp. 390–394, 2021, doi: 10.1109/WiSPNET51692.2021.9419442.

[72] M. S. Saud, H. Chowdhury, and M. Katz, “Heterogeneous software-defined networks: Implementation of a hybrid radio-optical wireless network,” in *2017 IEEE Wireless Communications and Networking Conference (WCNC)*, 2017, pp. 1–6.

[73] W. Networks, X. Wu, M. Safari, H. Haas, and S. Member, “Access Point Selection for Hybrid,” vol. 65, no. 12, pp. 5375–5385, 2017.

[74] X. Li, R. Zhang, and L. Hanzo, “Optimization of visible-light optical wireless systems: Network-centric versus user-centric designs,” *IEEE Commun. Surv. \& Tutorials*, vol. 20, no. 3, pp. 1878–1904, 2018.

[75] M. Z. Chowdhury, M. K. Hasan, M. Shahjalal, M. T. Hossan, and Y. M. Jang, “Optical Wireless Hybrid Networks: Trends, Opportunities, Challenges, and Research Directions,” *IEEE Commun. Surv. Tutorials*, vol. 22, no. 2, pp. 930–966, 2020, doi: 10.1109/COMST.2020.2966855.

[76] M. R. Ghaderi, “LiFi and Hybrid WiFi/LiFi indoor networking: From theory to practice,” *Opt. Switch. Netw.*, vol. 47, 2023, doi: 10.1016/j.osn.2022.100699.

[77] J. Vucic *et al.*, “125 Mbit/s over 5 m wireless distance by use of OOK-modulated phosphorescent white LEDs,” in *2009 35th European Conference on Optical Communication*, 2009, pp. 1–2.

[78] J. Vučić *et al.*, “230 Mbit/s via a wireless visible-light link based on OOK modulation of phosphorescent white LEDs,” in *2010 Conference on Optical Fiber Communication (OFC/NFOEC), collocated National Fiber Optic Engineers Conference*, 2010, pp. 1–3.

[79] M. Karlsson and E. Agrell, “Multilevel pulse-position modulation for optical power-efficient communication Abstract :,” *Opt. Express*, vol. 19, no. 26, pp. 799–804, 2011.

[80] H.-J. Jang, J.-H. Choi, Z. Ghassemlooy, and C. G. Lee, “PWM-based PPM format for dimming control in visible light communication system,” in *2012 8th International Symposium on Communication Systems, Networks \& Digital Signal Processing (CSNDSP)*, 2012, pp. 1–5.

[81] H.-D. Moon and S.-Y. Jung, “Multi-coded variable PPM for high data rate visible light communications,” *J. Opt. Soc. Korea*, vol. 16, no. 2, pp. 107–114, 2012.

[82] S. Dimitrov, S. Sinanovic, and H. Haas, “Signal shaping and modulation for optical wireless communication,” *J. Light. Technol.*, vol. 30, no. 9, pp. 1319–1328, 2012, doi: 10.1109/JLT.2012.2188376.

[83] J. F. Li, Z. T. Huang, R. Q. Zhang, F. X. Zeng, M. Jiang, and Y. F. Ji, “Superposed pulse amplitude modulation for visible light communication,” *Opt. Express*, vol. 21, no. 25, pp. 31006–31011, 2013.

[84] J. Armstrong, “OFDM for optical communications,” *J. Light. Technol.*, vol. 27, no. 3, pp. 189–204, 2009.

[85] S. C. J. Lee, S. Member, S. Randel, F. Breyer, S. Member, and A. M. J. Koonen, “PAM-DMT for Intensity-Modulated and Direct-Detection Optical Communication Systems,” vol. 21, no. 23, pp. 1749–1751, 2009.

[86] R. Meslehz, H. Elgalaz, and H. Haas, “An overview of indoor OFDM/DMT optical wireless communication systems,” *2010 7th Int. Symp. Commun. Syst. Networks Digit. Signal Process. CSNDSP 2010*, pp. 566–570, 2010, doi: 10.1109/csndsp16145.2010.5580369.

[87] Y. Li, D. Tsonev, and H. Haas, “Non-DC-biased OFDM with optical spatial modulation,” in *2013 IEEE 24th annual international symposium on personal, indoor, and mobile radio communications (PIMRC)*, 2013, pp. 486–490.

[88] B. Ranjha and M. Kavehrad, “Hybrid asymmetrically clipped OFDM-based,” *J. Opt. Commun. Netw.*, vol. 6, no. 4, pp. 387–396, 2014, doi: 10.1364/JOCN.6.000387.

[89] M. S. Islim, D. Tsonev, and H. Haas, "Spectrally enhanced PAM-DMT for IM/DD optical wireless communications," *IEEE Int. Symp. Pers. Indoor Mob. Radio Commun. PIMRC*, vol. 2015-Decem, pp. 877–882, 2015, doi: 10.1109/PIMRC.2015.7343421.

[90] S. M. Hardan, O. Bayat, and A. A. Abdulkafi, "A new precoding scheme for spectral efficient optical OFDM systems," *Opt. Commun.*, vol. 419, no. March, pp. 125–133, 2018, doi: 10.1016/j.optcom.2018.03.030.

[91] T. Zhang, H. Ji, Z. Ghassemlooy, X. Tang, B. Lin, and S. Qiao, "Spectrum-Efficient Triple-Layer Hybrid Optical OFDM for IM/DD-Based Optical Wireless Communications," *IEEE Access*, vol. 8, pp. 10352–10362, 2020, doi: 10.1109/ACCESS.2020.2964792.

[92] B. Li, X. Xue, S. Feng, and W. Xu, "Layered Optical OFDM with Adaptive Bias for Dimming Compatible Visible Light Communications," *J. Light. Technol.*, vol. 39, no. 11, pp. 3434–3444, 2021, doi: 10.1109/JLT.2021.3067495.

[93] T. Van Luong *et al.*, "Deep Learning-Aided Optical IM/DD OFDM Approaches the Throughput of RF-OFDM," *IEEE J. Sel. Areas Commun.*, vol. 40, no. 1, pp. 212–226, 2022, doi: 10.1109/JSAC.2021.3126080.

[94] A. A. Abdulkafi, S. M. Hardan, O. Bayat, and O. N. Ucan, "Multilayered optical OFDM for high spectral efficiency in visible light communication system," *Photonic Netw. Commun.*, vol. 38, no. 3, pp. 299–313, 2019, doi: 10.1007/s11107-019-00863-x.

[95] N. Huang, J. B. Wang, J. Wang, C. Pan, H. Wang, and M. Chen, "Receiver design for PAM-DMT in indoor optical wireless links," *IEEE Photonics Technol. Lett.*, vol. 27, no. 2, pp. 161–164, 2015, doi: 10.1109/LPT.2014.2363876.

[96] T. Zhang, Y. Zou, J. Sun, and S. Qiao, "Design of pam-dmt-based hybrid optical ofdm for visible light communications," *IEEE Wirel. Commun. Lett.*, vol. 8, no. 1, pp. 265–268, 2019, doi: 10.1109/LWC.2018.2869598.

[97] D. Tsonev, S. Sinanovic, and H. Haas, "Complete modeling of nonlinear distortion in OFDM-based optical wireless communication," *J. Light. Technol.*, vol. 31, no. 18, pp. 3064–3076, 2013.

[98] L. Sboui, Z. Rezki, A. Sultan, and M. S. Alouini, *IEEE Wirel. Commun.*, vol. 26, no. 3, pp. 168–174, 2019, doi: 10.1109/MWC.2019.1800161.

[99] R. Ariana, "済無No Title No Title No Title," pp. 1–23, 2016.

[100] A. H. Robbins and W. C. Miller, *Circuit analysis: Theory and practice*. Cengage Learning, 2012.

[101] A. W. Azim, Y. Le Guennec, and G. Maury, "Hermitian symmetry free optical-single-carrier frequency division multiple access for visible light communication," *Opt. Commun.*, vol. 415, pp. 177–185, 2018.