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Design an Outdoor Light Fidelity (Li-Fi) System Based on All-Optical OFDM Architecture

Marwa Jaleel Mohsin[1,2]* **Ibrahim A. Murdas**[1]

[1]*Electrical Engineering Department, College of Engineering, University of Babylon, Hilla, Babil, Iraq*
[2]*Engineering Technical College, Al-Furat Al-Awsat Technical University, Al-Najaf 31001, Iraq*
* Corresponding author's Email: marwa.jaleel@atu.edu.iq

Abstract: To overcome the RF spectrum crunch in the wireless communication networks and perform high-speed transmission with increased channel capacity, Light fidelity (Li-Fi) was presented by Harald Haas as a promising technology for the fifth generation and beyond. A high-speed Li-Fi system based on all-optical orthogonal frequency division multiplexing (AO-OFDM) was proposed and simulated in this paper. The optical signal was transmitted through a Free-space optical channel link making the proposed system suitable for outdoor application. All-optical OFDM architecture was improved the overall system performance. The 8 and 16 subcarriers were multiplexed demultiplexed through optical inverse fast Fourier transform/fast Fourier transform (OIFFT/OFFT) for the purpose of orthogonality. Optical IFFT was implemented at the transmitter side based on an optical frequency comb generator (OFCG) and dense wavelength division multiplexing (DWDM), while at the receiver side, Optical FFT was implemented based on multi-Mode interferometers (MMI) and time delays. The system was simulated by the VPI photonic design suite and analysed in terms of BER, Constellation diagram, and received power with different FSO path links from 1 to 100Km. Our system achieved a well-received power with high data rate reaches 1.2Tbps and low BER about 1×10^{-12}.

Keywords: Li-Fi, OFDM.O-OFDM, AO-OFDM, OFCG, OIFFT/OFFT, MMI.

1. Introduction

Optical wireless communication (OWC) is an ultrafast network presented in recent years to accommodate the reduction of Radio Frequency (RF) availably on the cusp of the 5th generation when the internet of things becomes an essential issue where life becomes data generated from machines but not from humans. These devices generate high data rates and are connected to the internet through wireless networks with resources RF or Wi-Fi. It causes a massive increase in network traffic and overcrowding of the RF spectrum, causing a spectrum crunch. OWC bearing the electrical signal on the optical carrier, by varying the intensity of the light can encode the data and transmitted signal through the atmosphere, characterized by unlimited throughput channel and existed everywhere. Since the light is faster than RF waves, it provides a massive data rate, enhancement for channel capacity, high spectral efficiency and more security. OWC utilized Infra-Red (IR), visible light communication (VLC), and ultraviolet (UV) frequencies of the electromagnetic spectrum (3-30000THz) [1, 2].

Li-Fi or optical Wi-Fi is a special kind of OWC that utilize IR and VLC band (3-790THz) approximately 2600 times of RF band (0.3THz). Fig. 1 shows the electromagnetic waves spectrum. In

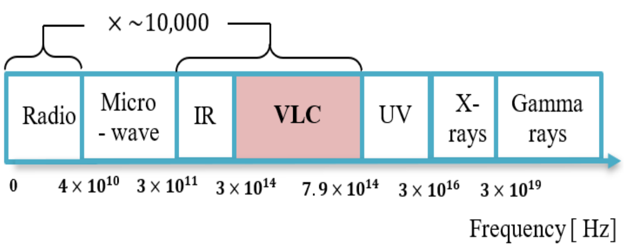

Figure. 1 Electromagnetic spectrum [1]

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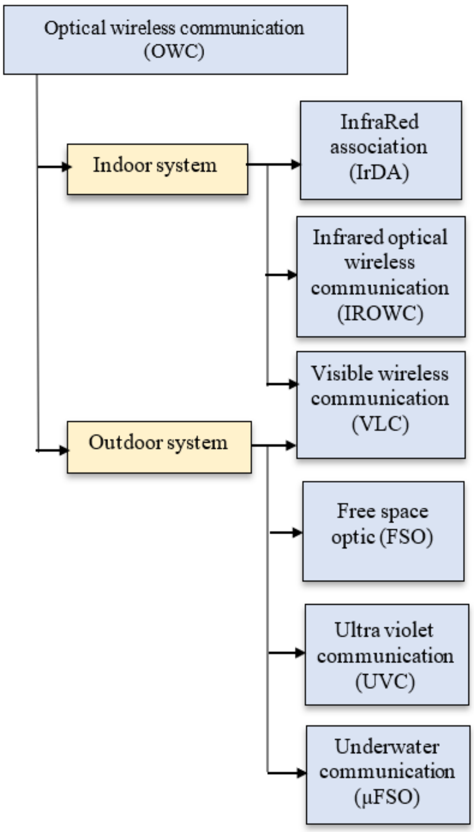

Figure. 2 OWC classification

principle, Li-Fi is similar to Wi-Fi, but it is more advantageous in terms of very high bandwidth, ultra-speed transmission, more spectral efficiency, and information security. Furthermore, Li-Fi may be used when Wi-Fi can't be used due to RF's interference with other waves, such as hospitals, factories, and airports, or in places where RF can't be utilized, such as underwater and mines [3,4]. Therefore, OWC can be classified as explained in Fig. 2.

Light emitting diodes (LEDs) and Laser diodes (LD) can be used as optical sources to modulate electrical signals in both indoor and outdoor applications. LED has a limited range and bandwidth of 10-20MHz, but LD can transfer data at a faster rate over a greater distance with Free space optic (FSO) and has a larger bandwidth of 10-20GHz, reduced power usage, and is more efficient [5].

Typically, Intensity modulation/Direct detection (IM/DD) was used to encode the intensity of the LEDs and laser diode. To encode large values of data with Li-Fi, Orthogonal Frequency Division Multiplexing (OFDM) was implemented, permitting multiuser to transmit the information simultaneously and provide simplicity with flexibility. On the other hand, OFDM provides immunity against inter-symbol interference resulting from the reflection of the light wave. The fundamental step in constructing OFDM is to accomplish orthogonality using Inverse Fast Fourier Transform/Fast Fourier transform (IFFT/FFT). OFDM is classified based on how the IFFT/FFT process is implemented: if the process is completely implemented in the electrical domain, it is known OFDM; if the process is completely implemented in the optical domain, it is all-optical OFDM (AO-OFDM); and if the process is hybrid between electrical and optical, it is known optical OFDM (O-OFDM). Moreover, O-OFDM was restricted with the symbol rate and bandwidth of the electrical components such as Analog-to-digital convertor/Digital-to-Analog convertor (ADC/DAC), serial -to-parallel (S/P), and parallel -to-serial (P/S). while with AO-OFDM, the orthogonality between the user was generated without the need for these electrical components [6, 7].

In this work, we designed and simulated a Li-Fi system suitable for outdoor applications with ultra-high data rate, maximum exploiting the channel capacity, and immune against the atmospheric attenuation due to utilized all-optical OFDM architecture. The transmission distance was increased (reaches 100 Km) by utilizing a Laser diode as an optical source rather than a traditional light-emitting diode LED. We success to generated many strong and high flatness of optical carriers from a single low power laser diode with fixed and tuneable spacing. The orthogonality was successfully created between these carriers after the modulation process by implementing inverse fast Fourier transform/fast Fourier transform (IFFT/FFT) completely in the optical domain. Our system shows a good performance compared with other previous works in terms of immunity, it presented low bit error rate BER about 1×10^{-12}, high data rate reaches to 1.2T bps which is generated from 8 and 16 orthogonal channels. The resulting signal was transmitted over the atmosphere channel with different path lengths.

This paper contains a survey for some previous works with its merits and demerits in Section 2, the outdoor Li-Fi system based all-optical OFDM architecture modelling with its general building block for the transmitter and the receiver sides are explained in detail in Section 3. Section 4, presented all required simulated results of our proposed system while Section 5 contains some concluding remarks of the system.

2. Literature review

Many previous studies were implemented Li-Fi systems for indoor and outdoor applications with different optical sources, modulation methods, and channel links. First, we provided a brief overview of some previous studies.

Reference [8] has used LEDs as optical sources to create an indoor Li-Fi system-based VLC, consisting of a series of Li-Fi access points mounted on the room ceiling and a backbone powered to allow the high-speed transmission to reach 5G optical wireless network targets. The access points are linked to the indoor getaway through a fiber backbone, and the indoor getaway is connected to the mobile network via an eNodeB macro-cell base station. Furthermore, to produce the delay between pulses, all-optical OFDM was constructed using a vector of optical delay line loops. This work presented a high BER with a small transmission distance due to using LEDs as an optical source.

Another researcher [9] simulated an outdoor Li-Fi system used a high-speed VLC system with a 20mW laser diode as an optical source and 4QAM-OFDM to transfer data at a bit rate of 10 Gbps across a distance of 250 metres. This work utilized OFDM in an electrical domain which limits the system bit rate to about 10Gbps. [10] presented a CO-OFDM system for FSO that could carry data across 220 metres in various weather situations. The system was simulated by Opti-system and evaluated good performance in terms of BER, constellation diagram, while the received power was typically low compared to our system. To enhance the system performance offered spatial diversity technique was utilized.

Reference [11] has created a laser-light Li-Fi system, using an integrated white light service mounted device to boost data rate and channel capacity. They employed QAM-OFDM to accomplish 11 Gb/s over a 5m distance with a single SMD and 1.7 Gb/s over a 50m distance with dual SMD and two-channel WDM; they reached 22.45 Gb/s over a 3m distance with dual SMD, and the two LD send data at the same time inside the wight light of MSD. The system was limiting the transmission distance to 5m and utilized electrical OFDM which limits the transmission data rate to 22.45 Gbps.

The necessity of Li-Fi as a highly timely technology owing to 6G for cellular connectivity prompted the researchers. Moreover, researchers [12] thought Li-Fi technology would complement the current Wi-Fi network (Wi-Fi). Thus, they created a hybrid Wi-Fi/Li-Fi system in the classroom that featured eight AP (Li-Fi attocell) that worked in tandem with the two existing Wi-Fi AP. The Li-Fi AP's circular coverage area is 2.5 to 3.5 metres. The system is characterized by a low data rate and limited to indoor applications only, it designed to support 8 persons at 43 Mbps for 344 Mbps per classroom. WDM-OFDM between four channels (four separate LED colours) increased data throughput and practicality while maintaining BER about 28×10^{-4} [7], this system presented a good performance with a low transmission distance of about 1.6m and was still limited by electrical components due to electrical OFDM.

3. Li-Fi based AO-OFDM system modelling

In this section, we demonstrate a high-speed outdoor Li-Fi system based on all-optical OFDM to increase the channel capacity and improve the received signal by using the light generated from a single continues laser (CW laser) as a source to optical frequency comb generator system to generate a set of shifted optical carriers to perform optical Fast Fourier transform (FFT) and produced AO-OFDM, the forward and reverse FFT considered as:

$$\varepsilon_m = \sum_{k=0}^{N-1} E_k \, e^{-i\frac{2\pi}{N}mk} \tag{1}$$

$$E_k = 1/N \sum_{m=0}^{N-1} \varepsilon_m \, e^{i\frac{2\pi}{N}km} \tag{2}$$

Where $E_k$is the frequency domain samples and ε_m is the time domain samples, m and K is the position,0 < m, k < N, where N is the total number of samples. While $t_m = m\tau$ and $\omega_k = k\delta$ represented the frequency and time position, respectively.

The generated subcarriers are bear the signals from 8 and 16 channels over a bandwidth 180 GHz and 340 GHz, respectively. The resulting signal with 8 and 16 orthogonal modulated signals is transmitted over free space channel link with different path lengths.

The proposed outdoor Li-Fi-based AO-OFDM architecture concept is shown in Fig. 3.

The system is simulated using VPI photonic design suite and evaluated the performance in terms of received optical power, BER, and the constellation diagram. Li-Fi based AO-OFDM system was classified into three stages: AO-OFDM transmitter, FSO channel, and AO-OFDM receiver. Each stage will explain in detail in the following sections.

3.1 AO-OFDM transmitter

To make all-optical OFDM symbols, the data generated by Pseudo random binary sequence generator (PRBS) was modulated with optical comb

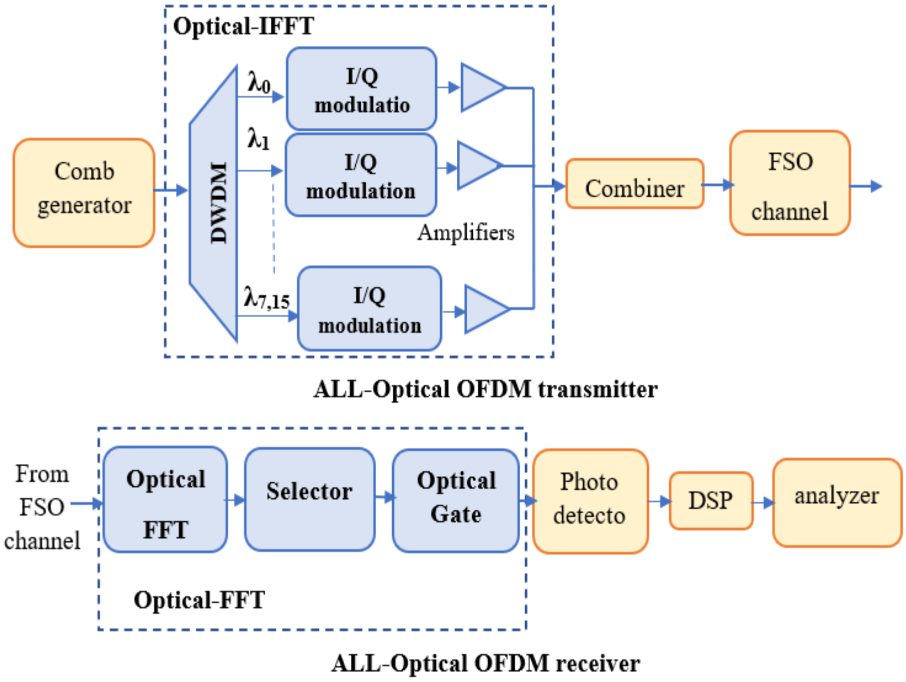

Figure. 3 Li-Fi based AO-OFDM system architecture

lines made by the optical frequency comb generator (OFCG) and sent into the air. Each channel sent a 20Gsymbol per second signal. The transmitter was divided into three parts, discussed in depth in the following sections.

3.1.1. Optical frequency comb generator (OFCG)

OFCG is an optical source with multi-wavelength can be advantageous to reducing the number of optical laser sources at optical line terminal (OLT) and providing multiuser with high bandwidth of data transmission. Several requirements must be available for OFCG: Generating stable frequencies (comb lines). Furthermore, an equal phase shift between these frequencies, and the spectral frequency of optical lines must be characterized by flatness [14]. The proposed OFCG was designed based on a single CW laser source, Amplitude modulator, two Mach-Zehnder modulators, RF signal generator, and phase shift. Fig. 4 explains the proposed OFCG design. The emission frequency of CW laser in VLC with 380THz ($f0$), and has an amplitude A_0 and phase φ_0. The probability density function is used to module the laser phase noise as:

$$f(\Delta\varphi) = \frac{1}{2\pi\sqrt{\Delta f dt}} \cdot e^{-\Delta\varphi^2 / 4\pi\Delta f dt} \qquad (3)$$

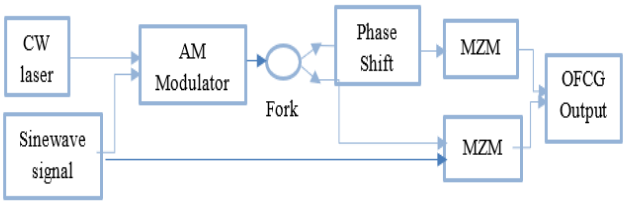

Figure. 4 OFCG architecture

Where $\Delta\varphi$ is the phase difference between two consecutive time instances and Δf is the line width of the laser diode [14].

The optical spectrum of CW laser has single optical carrier with a centre frequency 380THz ($f_0 = 380THz$). Due to amplitude modulation, the sideband become stronger. The output of AM was feed in to two parallel Mach-Zehnder modulator (MZM). MZM1 has received the signal of AM modulator after passing through phase shift which was placed to increase the bandwidth of OFCG, while another MZM2 receive this signal directly. The output of two MZM was companied using optical bus results set of optical carriers with spacing can be adjustable by varying RF signal frequency.

3.1.2. Optical IFFT

It is possible to get AO-OFDM by using inverse fast Fourier transform (IFFT) only in the optical domain and not with electrical parts. The key technique of creating optical IFFT at the transmitter side for orthogonality is by making the modulation

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baud rate of the channels equal to the spacing between the optical comb lines created from OFCG. Fig. 3 illustrates the optical IFFT (OIFFT) phases. All-optical OFDM signal was generated based on:

DWDM: The OFCG signals were demultiplexed using DWDM, containing eight or sixteen bandpass filters with Gaussian transfer function. The centre frequency of the DWDM band pass filter separated by 20GHz, which is represented f_c . Demultiplexed the comb lines results sub-carrier's frequencies (Nch); each frequency represents the optical carrier for single-channel and will be input to the modulators.

Dual polarization IQ modulation: Each channel encoded data generated from PRBS with a data rate of 20Gsymbol/s on its optical sub-carrier. Dual polarization IQ (In-phase/Quadrature of phase) modulator was utilized with QPSK and QAM symbols.

Optical Amplifier and combiner: Each sub-channel output signal amplified using an optical amplifier with a maximum gain of 30 dB. OFDM symbols are generated by combining the channels' output using optical power. The result an orthogonal eight or sixteen sinc optical spectrum signal and ready to transfer it using optical oscilloscope through free-space optical channel.

3.2 All-optical OFDM receiver

After passing the signal through the FSO channel with different path length, the received signal was subjected to a set of optical couplers and delayer to implement All-optical FFT before being All-optical OFDM receiver was classified into four sub-stages:

3.2.1. Optical FFT

All-optical FFT implemented by utilizing set of optical multi-mode interferometers (MMI) and optical delays.

Multi-mode interferometer MMI is a device that distributes optical power from one or several input ports among several output ports and is based on destructive/constructive interferences occurring in the MMI area with many guided modes. MMI have many potential applications such as couplers, splitters, combiners, mode converters, filters, etc. Fig. 5 explains the optical FFT utilized based MMI and time delayers. We have implemented 8 & 16-Optical FFT for eight and sixteen channels. Figure (5a) explains 8-OFFT, the first stage of optical delay has TS/2-time delay while in the second stage, each delayer has TS/8-time delay.

Conversely, 16-OFFT was explained in figure (5b), the first stage optical delays, have TS/2-time delay, while the second stage optical delays have TS/4-time delay and third stage TS/16-time delay.

3.2.2. Optical gate

The sampling process can perform using optical gates. The sampling gates can be located at the beginning before OFFT or the end of the system after OFFT without changing overall system performance. The optical gates are designed using:

- Pseudorandom binary sequence generator: Generated random bits with bit rate equal to the system baud rate (20Gsps),
- On Off code driver: with modulation type RZ Time delay.
- AM modulator.

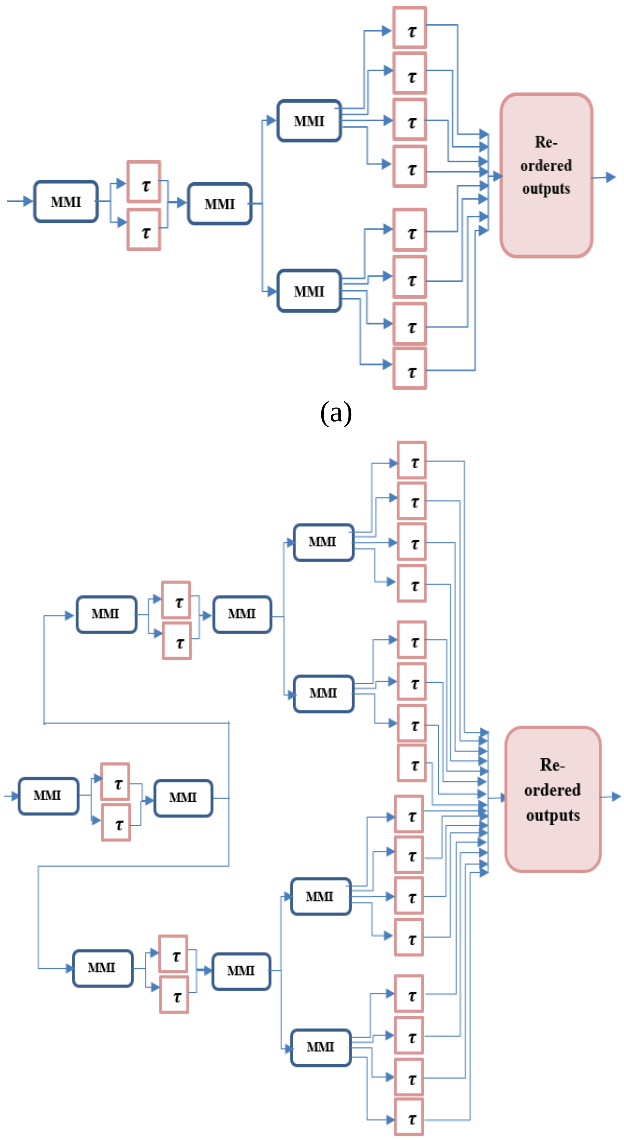

Figure. 5 Optical FFT architecture at receiver side

3.2.3. Dual polarization receiver

The coherent receiver was used for detecting IQ components to detect the received signal. First, a local isolator was used with a frequency equal to emission laser frequency to change the phase of the local oscillator by 90 degrees. Then, a hybrid optical network was utilized to feed a signal into eight photodetectors to convert the optical signal to electrical and then analogue to digital convertors.

3.2.4. Digital signal processing

A single-carrier coherent transmission DSP library-based Python was used. The module processes signal samples represented as a floating matrix. A row of the matrix contained samples of [I Q] signal components for 2D and [Ix, Qx, Iy, Qy] signal components for 4D modulations. The module received the input sampling rate and output the postprocessing sampling rate as a float number. The DSP algorithms were implemented: 16QAM phase estimation and QPSK. The recovered signal has good BER with a clear constellation diagram.

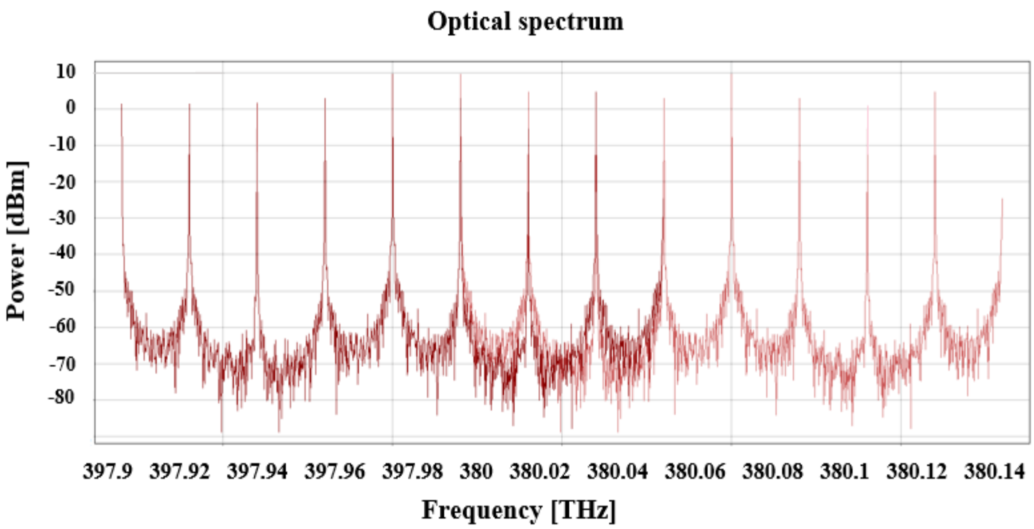

Figure. 6 Frequency spectrum of OFCG with frequency spacing 20GHz

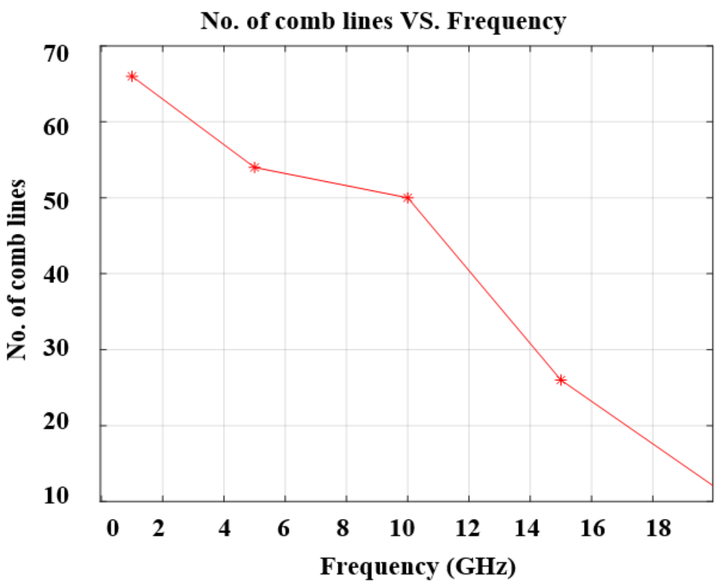

Figure. 7 RF signal frequency vs. no. of comb lines

4. Simulated results for the proposed system

4.1 For transmitter

A Li-Fi system based on All-optical OFDM for

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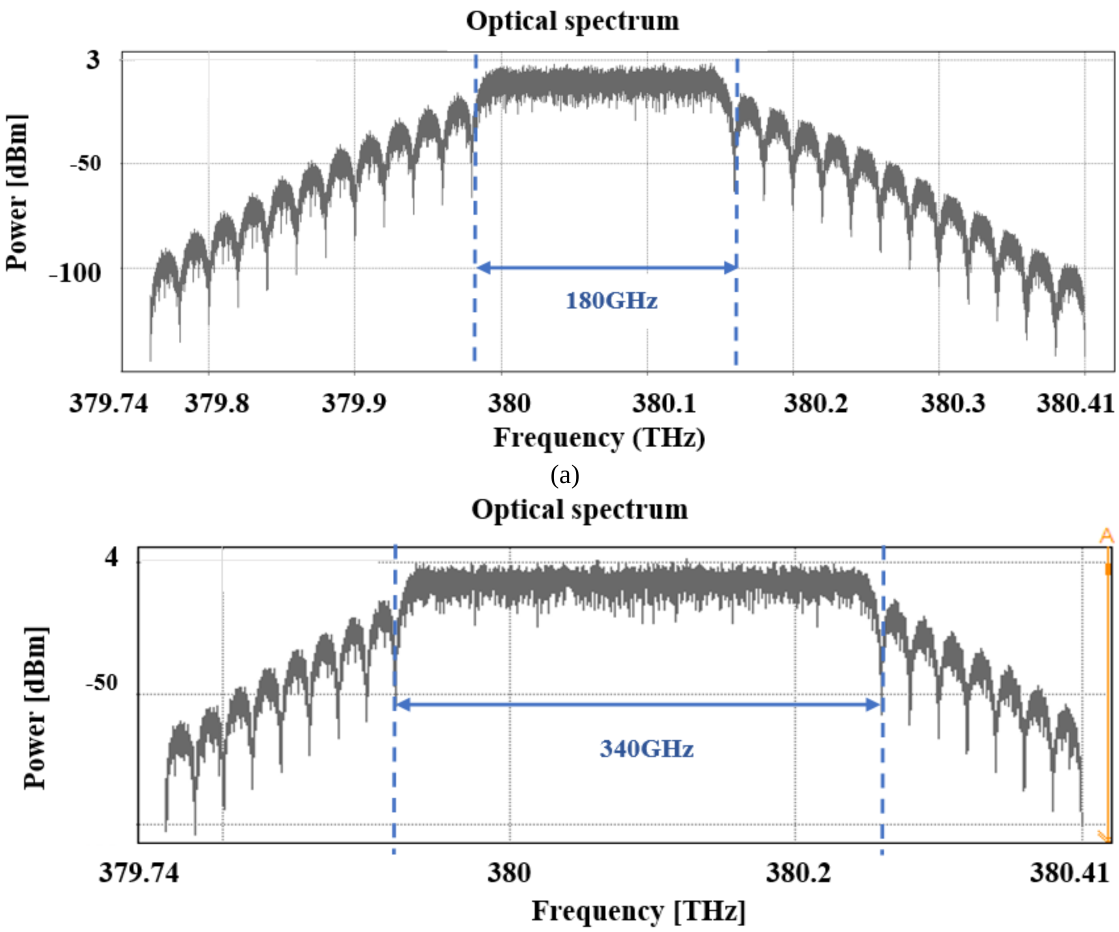

(b)

Figure. 8 Frequency spectrum of AO-OFDM signal: (a) 8 channel and (b)16 channel

free-space-optical communication applications was presented in this work. We considered LD as an optical carrier source for VLC rather than traditional LED due to the growing urgency for a higher data rate. OFCG based CW laser source, CW laser with emission frequency 380THz (on VLC band) and power 1mW. OFCG generated set of optical carriers over 220GHz bandwidth, the central frequency f_0 = 380THz and spacing fs=20GHz. These spacing can be adjusted by varying RF signal wave frequency. The generated comb lines reached 42 and were characterized by their flatness and strong about 0dBm with fluctuation of less than 0.5 dBm.

Fig. 6 explains the spectrum frequency of OFCG system with centre frequency lines 380THz and frequency spacing 20GHz (the RF signal frequency). By increasing RF signal frequency, the spacing between comb lines was increased simultaneously, and the number of comb lines decreased. Fig. 7 shows the relationship between number of the generated comb lines with RF signal generator frequency, while Table 1 explains the proposed OFCG system parameters.

Table 1. The parameter of proposed OFCG system

The device	Parameter	Value
CW laser	Emission frequency	380THz
	Output power	1mW
	Line width	100KHz
	Azimuth	45 deg
RF signal generator	Frequency	5,10,20 GHz
	Amplitude	2 a.u.
	Bias	1 a.u.
AM modulator	Modulation index	1
Phase shift	Frequency offset	100GHz
MZM1, MZM2	Extinction ratio	35dB
	Chirping factor (α)	5
OFCG	Bandwidth	220GHz

The comb lines with spacing 20GHz were demultiplexed with DWDM into 8 and 16 subcarriers. Each subcarrier, after demultiplexing represented the optical carrier of single-channel, each channel modulated its data by dual polarization I/Q modulator with 2 and 4 bits per symbol

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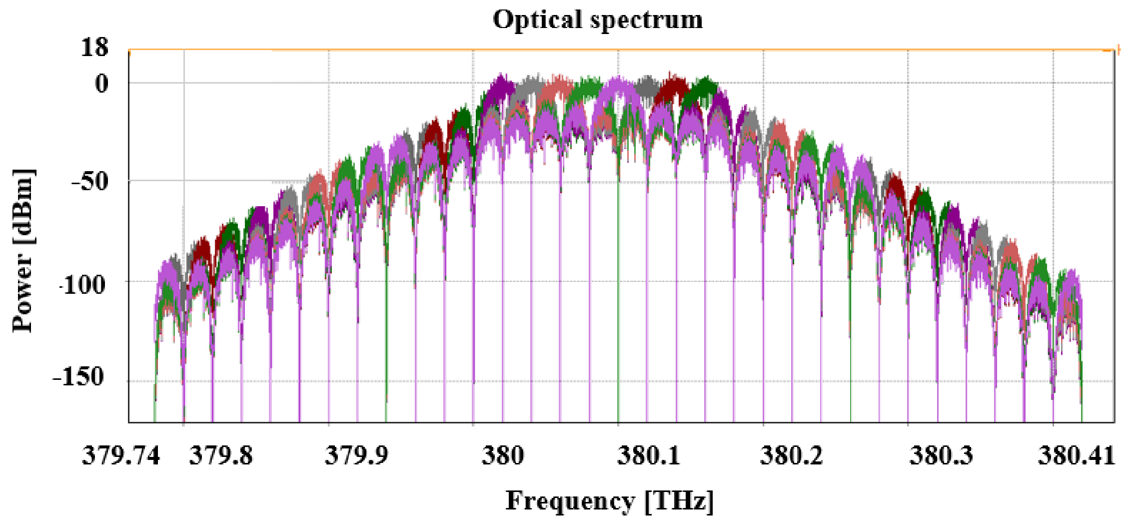
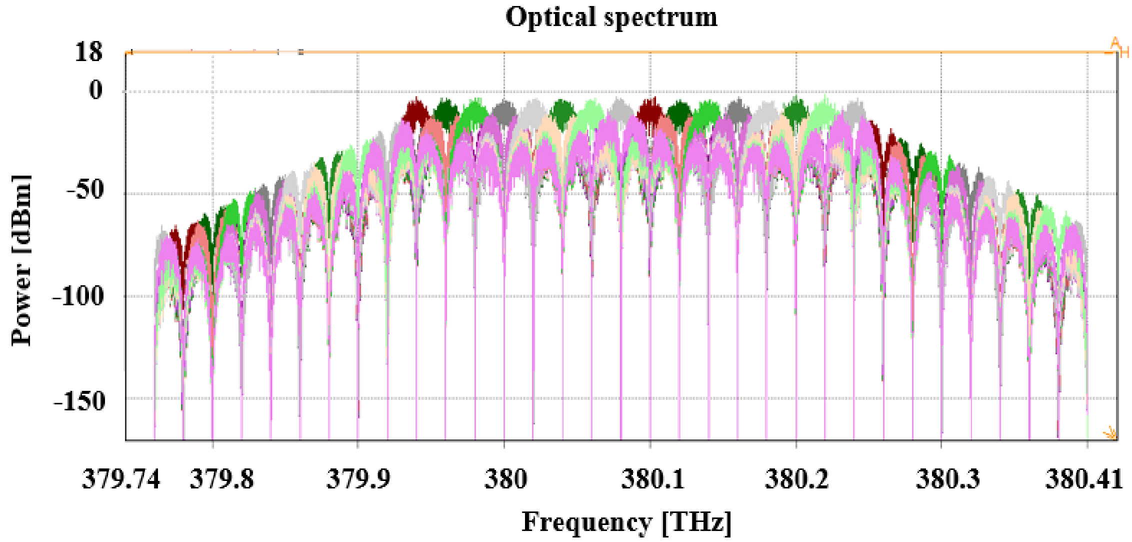


(a)



(b)

Figure. 9 Optical FFT: (a) 8-OFFT and (b) 16-FFT

Table 2. The parameters of Li-Fi based AO-OFDM transmitter

The device	Parameter	Value
DWDM	Filter type	Bandpass
	Filter function	Gaussian
	Bandwidth	1e9 Hz
	Centre frequency spacing	20GHz
	No. of channel	8,16
IQ Modulation	Sample rate	4.6e11 Hz
	Baud rate	20e9 Hz
	Bit per symbol	2, 4 Bits
Amplifier	Amplifier type	Power control
	Output power	1W
	Maximum gain	30dB
Transmitted	Output power	3dBm
	Bandwidth	180,340 GHz
	Sample rate	640GHz

(QPSK, 16-QAM). AO-OFDM symbols were generated by combining the output of the eight or sixteen channels using an optical combiner and transmitted to propagated through Line-of-sight FSO channel link. The frequency spectrum of the transmitted signal with 8,16 channels was explained in Fig. 8. Table 2 explains the transmitter parameters of Li-Fi system-based AO-OFDM architecture.

4.2 For receiver

After passing through the FSO channel with 10-100Km LOS path length, the received signal was utilized into optical 8-OFFT and 16-OFFT. After that, the selector was used to select the desired channel for the sampling process. The sampling process was performed using the optical gate and

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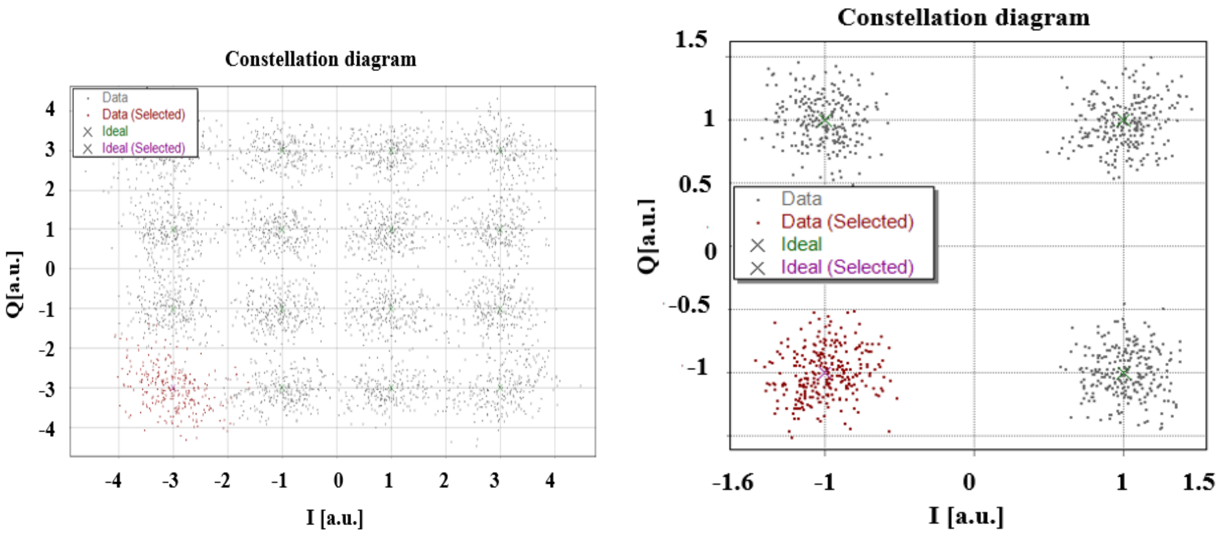

(a) (b)

Figure. 10 constellation diagram of received signal after DSP: (a) QPSK and (b)16-QAM

Table 3. The al-optical OFDM receiver parameters

The device		parameter	value
Receiver		dimeter aperture	10 cm
8-OFFT		Symbol rate Ts	25e-12
		No. of MMI	6
		No. of time delays	10
16-OFFT		Symbol rate Ts	25e-12
		No. of MMI	16
		No. of time delays	22
Optical Gate	**PRBS**	Baud rate	20GHz
	OOK driver	Bite rate	20Gbps
		Sample rate	640GHz
		Transition time	0.45/20e-9
	Time delay	Delay time	0.45/20e-9
	AM modulator	Modulation index	1

Table 4. The overall Li-Fi system-based AO-OFDM parameters

Parameter	value	
Data rate for single channel	20 G symbol/s	
Sample rate	640GHz	
No. of channels	8,16	
Operating centre frequency	380GHz	
Link range	10-100K(m)	
Channel spacing	20GHz	
Modulation technique	AO-OFDM	
Modulation scheme	QPSK,16-QAM	
Laser type	CW	
No. of laser source	One	
No. of bit per symbol	2, 4	
Bit rate	QPSK & 8-OFFT	$2 \times 8 \times 20G =$ 320 Gbps
	16-QAM & 8-OFFT	$4 \times 8 \times 20G =$ 640 Gbps
	QPSK & 16-OFFT	$2 \times 16 \times 20G$ = 640 Gbps
	16-QAM & 16-OFFT	$4 \times 16 \times 20G$ = 1.28 Tbps

then applied to the photodetector. It produced an electrical signal using DSP to recover the original signal. Fig. 9 shows the signal after OFFT. While Fig. 10 illustrates the consultation, Dignam of QPSK and 16-QAM received signal for proposed Li-Fi based AO-OFDM architecture.

All-optical OFDM receiver parameters are illustrated in the Table 3. The overall proposed Li-Fi based All-optical OFDM system parameters are explained in Table 4.

Our system was tested under different SNR and path lengths with observed the effect on system BER and received signal power. Table 5 shows SNR vs BER for both 8-OFFT and 16-OFFT, while Fig. 11 shows this relation. BER for a different path length of the Li-Fi system was explained in Table 6.

Generally, the Li-Fi system based all-optical OFDM architecture has better performance for QPSK and 8-OFFT than 16QAM and 16-OFFT in

Table 5. SNR vs. BER for 8-OFFT and 16-OFFT

SNR(dB)	BER			
	QPSK		16-QAM	
	8-FFT	16-FFT	8-FFT	16-FFT
0	0.7	2.4	1.8	3.1
5	0.01	1.7	0.86	1.06
10	8e-4	8e-2	3.2e-2	0.2
15	6.3e-6	4.6e-2	5.1e-3	6e-2
20	2e-8	9.1e-3	8.5e-5	2.5e-3
25	3.5e-10	7.7e-3	3.2e-6	7.7e-3
30	8.5e-11	4.3e-5	8e-6	6.4e-4
35	1.07e-14	9.7e-6	3.2e-8	7.2e-4

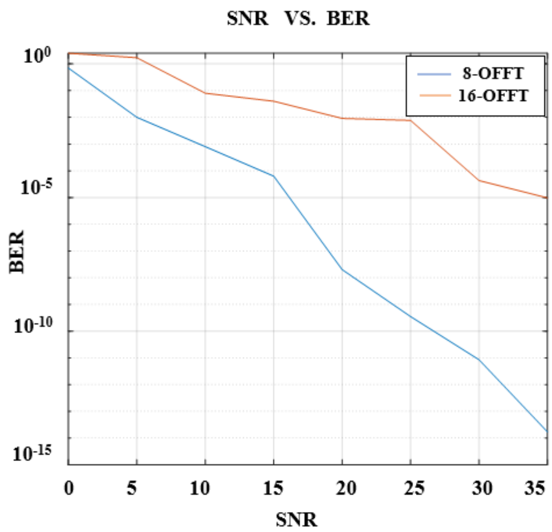

Figure. 11 SNR vs. BER for 8-OFFT and 16-OFFT with QPSK

BER. The proposed system was characterized by a high data rate ranging from 320Gbps to 1.28Tbps, as shown in Table 4 and a good received signal for different path-length as shown in Table 6. Table 7 shows the compression of the proposed system with other previous work.

5. Conclusion:

We demonstrated an ultra-high-speed Li-Fi system based on all-optical OFDM architecture. The system was more suitable for outdoor applications and its immune against atmospheric attenuation due to utilizing all-optical orthogonal frequency division multiplexing (AO-OFDM). We utilized laser diode as optical sources to maximize the transmission distance through free space channel links (reaches 100Km) and to overcome the limitation of traditional LEDs. We designed an optical frequency comb generator (OFCG) to generate about 42 strong and flat subcarriers from a single low power laser diode (1mW) over a 220 GHz of bandwidth for optical multiplexing/demultiplexing, the spacing between these subcarriers are fixed and tuneable. We successfully implemented IFFT/FFT completely in the optical domain between 8 and 16 channels to create the orthogonality with 20 GHz channels spacing. This paper implemented an All-optical OFDM system based on an optical frequency comb generator (OFCG) with dense wave division multiplexing (DWDM) for inverse Fourier transform (IFFT) at transmitter and multi-mode interferometer (MMI) with time delay for fast Fourier transform (FFT) at the receiver. Our system shown a good performance compared with previous studies in terms of high bit rate reaches 1.2Tbps, low BER about 1×10^{-12}, and strong received power, the received power ranging between 2 and -25 dBm with the different free space optic FSO -line of sight (LOS) path links (1-100Km).

Conflicts of the interest

The authors declare no conflict of interest.

Authors Contributions

The authorship of this paper is based on the following criteria: conceptualization, Marwa Jaleel Mohsin and Ibrahim A. Murdas; methodology, Marwa Jaleel Mohsin; software, Marwa Jaleel Mohsin; validation, Marwa Jaleel Mohsin and Ibrahim A. Murdas; formal analysis, Ibrahim A. Murdas; investigation, Marwa Jaleel Mohsin; resources, Marwa Jaleel Mohsin; data curation, Marwa Jaleel Mohsin; writing—original draft preparation, Marwa Jaleel Mohsin; writing—review and editing, Ibrahim A. Murdas; visualization, Marwa Jaleel Mohsin; supervision, Ibrahim A. Murdas; project administration, Marwa Jaleel Mohsin and Ibrahim A. Murdas; funding acquisition, Marwa Jaleel Mohsin.

Table 6. received power with BER under different FSO-LOS path length

FSO path length (Km)	Received power(dBm)	BER
1	2.07	1.09e-12
10	1.29	5.25e-12
20	-2.97	9.67e-10
30	-7.96	3.21e-9
40	-10.09	6.43e-9
50	-11.59	1.04e-8
60	-12.7	3.54e-8
70	-13.66	9.51e-8
80	-14.44	3.21e-7
90	-23.06	4.37e-7
100	-25.88	5.09e-7

Table 7. The compression between previous studies and our work

Ref.	Optical source	Channel type	OFDM type	No. of channel	Modulation scheme	Received optical power (dBm)	Bit rate (bps)	Distance (Km)	BER
[7]	LED	indoor	Electrical	-	WDM-OFDM	-	15.73G	1.6m	28×10^{-4}
[8]	LEDs	Indoor	Optical	4	-	-	-	-	1×10^{-3}
[9]	LD	Outdoor	Electrical	-	4-QAM	-60	10G	250m	-
[10]	LD	Outdoor	Electrical	512	QAM	-30		100Km	-
[11]	LDS (SMD)	Outdoor	Electrical	-	16-32-64 QAM	-	22.45G	5-50m	2.98×10^{-3}
[12]	LED	indoor	-	8 users	-	-	344M	2.5-3.5m	-
Our	LD	Outdoor	Optical	8-16	QPSK,16-QAM	-2	1.2T	1-100Km	1.09×10^{-12}

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