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RESEARCH ARTICLE

Simulation Investigation of Symmetric 8 × 25Gbps Hybrid TWDM-DFMA PON for Long-Reach Applications

MEET KUMARI[1], VIVEK ARYA[2], AND HAMZA MOHAMMED RIDHA AL-KHAFAJI[3], (Senior Member, IEEE)

[1]Department of Electronics and Communication Engineering, Chandigarh University, Mohali, Punjab 140413, India
[2]Department of Electronics and Communication Engineering, Faculty of Engineering and Technology, Gurukula Kangri (Deemed to be University), Haridwar 249404, India
[3]Biomedical Engineering Department, College of Engineering and Technologies, Al-Mustaqbal University, Hillah, Babil 51001, Iraq

Corresponding author: Hamza Mohammed Ridha Al-Khafaji (hamza.alkhafaji@uomus.edu.iq)

ABSTRACT By utilizing digital filter multiple access (DFMA) technique in the optical access networks allows immense potential to offers superb backward compatibility with existing optical as well as forthcoming cloud access networks. Time and wavelength division multiplexing passive optical network (TWDM-PON) incorporating DFMA depicts the promise of absolute and economical optical access networks for 5G based long-reach high speed applications. This simulation work in OptiSystem software, presents a bidirectional hybrid TWDM-DFMA PON system at 25Gbps data rate employing eight uplink and eight downlink channels for long-reach applications. The advantage of this work is to provide a high-bandwidth as well as advanced last-mile network having adequate resource utilization for fiber links. The minimal received power of –19dBm in uplink as well as –14dBm in downlink transmission can be obtained by the proposed system over 50km fiber length at 200Gbps data rate. The system offers faithful data transmission over 150km and 100km in uplink and downlink directions, respectively, over a single fiber link. Further, the system can support end optical units up to 250 in uplink and 120 in downlink successfully. Moreover, a power budget improvement of 4dB and a maximum optical signal to noise ratio (OSNR) of 91dB can be obtained for the system. Besides this, the proposed PON is most efficient compared to other conventional PONs in terms of less energy consumption, better spectral usage, long-reach transmission at high data rate and ability to handle large number of end users.

INDEX TERMS Digital filter multiple access (DFMA), passive optical network (PON), time and wavelength division multiplexing (TWDM).

I. INTRODUCTION

The explosive growth in Internet traffic has substantially enhanced the high bandwidth demand connectivity in both residential and industrial speculations. The existing worldwide breathtaking 5G network development strengthens for instance tendency and leads a number of additional terrific technical issues, including elastic and flexible functionality, dynamic configurability, improved installation cost-effectiveness as well as reduced network simplicity. To furnish dynamically reconfigurable, reliable, flexible, transparent, smart, secure and high-performance environs to satisfy rigid conditions, it is necessary to smoothly cover conventional optical networks, mobile fronthaul or backhaul access networks, which have been individually developed and severally operated over the last few decades [1], [2].

Passive optical network (PON) is considered globally as one of the most feasible prospects for recognizing the elegant network convergence. It is notable that conventional PON access networks are becoming inappropriate to successfully accommodate the rising high effectual data traffic patterns. Further, future time and wavelength division multiplexing

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PONs (TWDM-PONs) are too expected to be accompanied with software defined networking (SDN) to offer elastic and reconfigurable on-demand inter-connects down to the lowest physical layer. To provide such required functionalities with acceptable transparency to primary network design characteristics, a new multiple access scheme termed digital filter multiple access (DFMA), which employs digital signal processing based, transceiver-embedded and SDN-rulable digital orthogonal filters to permit dynamically elastic as well as reconfigurable physical interconnections between optical network units (ONUs) and central office to fulfil transient network traffic requirements. The working principle and main advantages of DFMA-PONs, such as network adaptability, backward compatibility, elasticity, flexibility, bandwidth utilization ability, cost-effectiveness, operation functionality, and power consumption adequacy over conventional PONs motivate for extended research developments interest in next-generation PONs based DFMA PONs [3], [4].

So, comprehensive works have been proposed for DFMA PONs. In [5], an all-optical virtual private network in DFMA PON using orthogonal frequency division multiplexing (OFDM) has been investigated. The results show that DFMA-OFDM PONs offers a transmission range of 25km in single mode fiber (SMF) with 2dB power penalty at 10^{-3} BER. This scheme also provides a favorable method for the power-saving and cost-effective applications of all PONs based on a virtual private network. But it limits the network expandability as well as upgradability as it suffers from SMF dispersion if the ONUs are set other than central frequencies. Besides this, the allocated different filters in the network need to be adjusted dynamically utilizing controllable SDN as per the traffic as well as users' transmission link characteristics. Also, the same network has been reported in references [1], [6], and [7], with a maximum data transmission rate of 13.125Gbps for 5G networks. However, in [1], the OFDM-DFMA PON system is proposed through theoretical predictions without any simulation or experimental investigations, thus lacks in the verification of the system in the practical access networks. To obtain the receiver sensitivity of less than 1dB, limited and shortest filter length of 16 is adopted in [6]. Also, it suffers from optical beating interference (OBI) noise in the OLT. Moreover, in [7], the transmission performance of the proposed system is demonstrated over limited range of 25km with restricted filter length of 64. However, in [3], a standard SMF (SSMF) distance up to 26km using intensity modulation and direct detection (IMDD) DFMA PONs with OFDM technique has been proposed, but it lacks in data rate of 0.625Gbps and maximum 12 frequency subcarriers are allowed to analyse the system performance. Additionally, an IMDD-DFMA PON employing DFMA channel interference cancellation scheme at 32.5Gbps transmission rate over 26km SSMF has been proposed in [8]. Moreover, in [9], a real-time experimental demonstration of 0.7Gbps hybrid OFDM DFMA-PON over 26km SSMF to provide SDN-controlled network reconfigurability and offer elastic bandwidth provisions as well as highly efficient usage of network resources has been reported. Although, both [8] and [9],lacks in limited data rate, cost-effectiveness and transmission distance. Additionally, DFMA PON in [10] and [4] has also been presented but with a restricted data rate of 0.75Gbps and SMF range of 26.5km. Further, the advanced approach used in [11], incorporating a four channels OFDM-based DFMA PON over 26km SMF at 50Gbps data rate, has been realized successfully with enhanced performance and robustness of network. Although, it produces additive white Gaussian noise generated from amplifier and photo-detector hence cause distorted constellation points. Furthermore, in [12], the data rate has been further increased to 101.6Gbps through experimental demonstration. But due to restricted transmission range of 25km, high system complexity and less flexibility, the OFDM-DFMA PON is not adequate for future access networks. Thus, to increase the SMF distance up to 50km, a 10Gbps IMDD-based hybrid OFDM-DFMA PON has been reported in [13]. However, the cancellation of cross-channel interference technique has not been realized in the system. In addition, a bidirectional hybrid TWDM-DFMA PON utilizing time division multiplexing and sub-band grouping techniques over a 25km SMF range at 15Gbps data rate has been proposed successfully, hence lacks in system transmission range as well as data rate [14].

Several previously presented research work, capable of realizing long-reach and high transmission rate in conventional DFMA-PONs, requires multiple additional transceiver and extra network resources, leading to massive modifications to traditional PONs architectures. Further, the past DFMA-PON designs also have limited transparency, upgradability and flexibility to future convergent networks incorporating an extensive variety of main network operation characteristics to be adapted. To handle the aforesaid issues cost-effectively, a bidirectional symmetric hybrid TWDM-DFMA PON for long-reach and high-capacity applications is proposed in this work. Compared with the earlier reported work, the proposed PON offers numerous advantages, such as a high transmission rate, less complex and cost-effective transmitter/receiver implementations [12], [15].

The novelty of this work is to design an energy-efficient, high-speed as well as long-reach symmetric hybrid TWDM-DFMA PON supporting large number of users. It is a future based 5G and cloud access network. The major contributions of this work are: to enhance the transmission distance against transmission impairments in fiber, enhance system throughput, minimizes considerable channel interference, reduces the energy consumption and improves cost-effectiveness over bidirectional transmission channel supporting huge number of ONUs. The performance of the proposed system has been measured in terms of bit error rate (BER) as well as received optical power under the impact of fiber impairments. The proposed work is systemized as follows. Section II defines the design of hybrid TWDM-DFMA PON system. Results and discussion are explained in Section III. Finally, Section IV illustrates the conclusion and future work of the proposed system.

II. PROPOSED DESIGN

The proposed architecture of the bidirectional hybrid TWDM-DFMA PON is presented in FIGURE 1. This architecture is comparable with the conventional TWDM-PON employing eight wavelengths in both uplink and downlink organization that ONUs and central office or optical line terminal (OLT) are linked via optical distribution network (ODN) which uses passive components like power splitter, power combiners, optical circulators etc. For downlink and uplink transmission, wavelengths ranging from 1596 to 1601.6nm and 1527 to 1532.6nm with 0.8nm channel spacing are utilized, respectively, at 25Gbps per channel data rate.

A digital signal processing (DSP) module is employed in an OLT and each ONU as shown in FIGURE 1(a). Also, to cope with optical beat interference problem, coherent detection with local oscillator (LO) laser are endorsed at OLT side. A continuous wave (CW) laser at uplink wavelength is allocated to each ONU for their uplink transmission. During uplink transmission, an ONU initially encodes its original information, and then Z extra zeros are introduced into each of two adjoining data samples at up-sampling factor $Z+1$ for up-sampling.After data sampling, a digital shaping filtering function is performed.Here, digital shaping filter impulse response is accepted by selecting in-phase (I) or quadrature (Q) phase component as well as adjusting central frequency f_c, which are considered as [14]:

$$g(t) = \begin{cases} c(t)\cos 2\pi f_c t\ (I-phase) \\ c(t)\sin 2\pi f_c t\ (Q-phase) \end{cases} \quad (1)$$

where

$$c(t) = \frac{\sin\left[\frac{\pi(1-\sigma)tf_{DAC}}{Z}\right] + \left(\frac{4\sigma tf_{DAC}}{Z}\right)\cos\left[\frac{\pi(1-\sigma)tf_{DAC}}{Z}\right]}{\pi t\left[1-\left(\frac{4\sigma tf_{DAC}}{Z}\right)^2\right]\frac{f_{DAC}}{Z}} \quad (2)$$

where the factor σ controls the excessive bandwidth of the filter, f_{DAC} means the digital to analog converter (DAC) sampling rate which the ONU incorporates. The central frequency f_c is defined as [14]:

$$f_c = \frac{(2a-1)f_{DAC}}{2Z+2} a\epsilon\,(1,2,3,\ldots),\ a \le \left(\frac{Z+1}{2}\right) \quad (3)$$

These operations are completed by the DSP module. Then a DAC, a radio frequency (RF) amplifier and a modulator are endorsed to module signals in upstream transmission. These signals generated from the laser placed at ONU side for different upstream wavelengths. Direct current (DC) bias voltage of 2.3Vis employed to cancel out the phase drifts that are evaluated utilizing the mach Zehnder modulator (MZM) output intensities of the analytic signals. After this, being integrated with other signals from other ONUs in ODN, the optical signals are transferred to the OLT as depicted

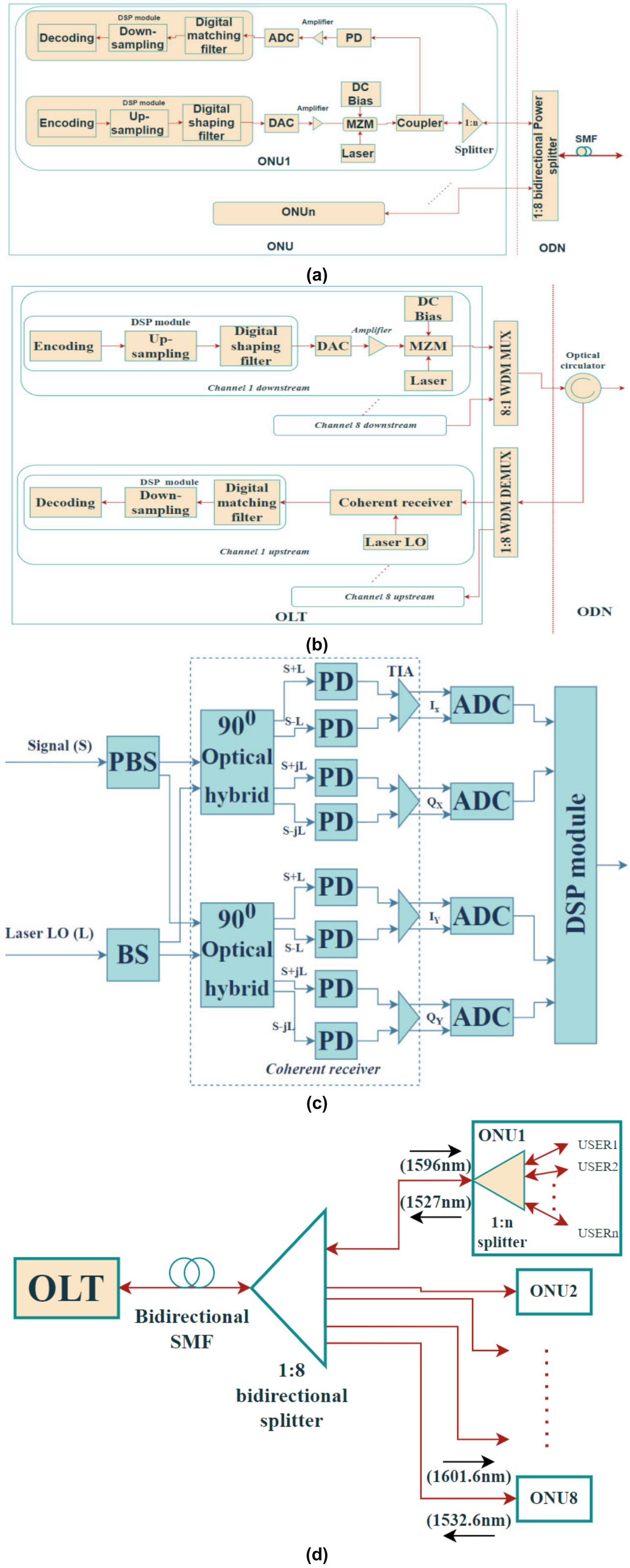

FIGURE 1. Schematic of a hybrid TWDM-DFMA PON (a) ONU & ODN sections, (b) OLT section, (c) setup of coherent receiver and (d) distribution architecture.

in FIGURE 1(a). As per, the intended ONU, the data is encoded and up-sampled followed by processing by digital shaping filters in DSP module. Then, all the uplink signals are assembled. Then the signals are modulated into uplink optical waves by a MZM with DC bias [14].

Further, the downlink transmission occurs on a distinct downlink optical wavelength. At ONU side, the downlink signals transfer to an optical coupler and a photo diode (PD) considering shot noise. Later, after jointly transmitting the signals to digital domain by PD, a RF amplifier and analog to digital converter (ADC), the ONU could retrieve its downlink data through formation of respective digital matching filter, down-sampling and decoding process. Also, ODN section consists of standard bidirectional SMF along with 1:n bidirectional power splitters passive components [14].

Furthermore, 8:1 wavelength division multiplexing (WDM) multiplexer and 1:8 WDM de-multiplexer are used for downlink signals transmission and uplink signals reception respectively, at OLT side as presented in FIGURE 1(b). An uplink receiver incorporates a coherent receiver with LO laser to enables precise electrical carrier recovery as well as symbol detection. After this, the collective signals from the optical to digital domain are conveyed to the DSP module. DSP module would join these signals and based on the phase and f_c parameters which the ONU acquires in the shaping filtering technique and sets up a digital matching filter having $h(t) = g(-t)$ impulse response in accordance to extract signals. The impulse eradicates the extra data samples to recover the data by a decoder. Eventually, after a down-sampling technique to mentioned which the data sampling rates of ADC and DAC are set to be alike. Besides this, the downstream channel consists of DSP module, bias, laser and modulator to offers downstream signal [2], [14]

FIGURE 1(c) presents the forward end of coherent receiver structure of the proposed system. From splitter, the received optical signals are mixed with the laser LO which operates at frequency offset of 15GHz with input laser at OLT and 10dBm output power. Polarization beam splitter (PBS) and beam splitter (BS) are used to forward the received signals from transmitter and LO respectively, to two 90^0 optical hybrid components. In coherent receivers, these 90^0 optical hybrid components are used to demodulate the phase-encoded signals. Then eight balanced PDs are employed to convert the optical signals into electrical signals. Four transimpedance amplifiers (TIAs) are employed to convert the current output to equivalent output voltage. Finally, the signals are digitalized through four ADCs and then processed in DSP module [16].

The received optical signal for X polarization at front end of coherent receiver is expressed as [16]:

$$E_x(t) = P_x(t)\exp[j(2\pi f_c t + \varphi_x(t))] \tag{4}$$

where $P_x(t)$ and $\varphi_x(t)$ mean modulated amplitude and phase respectively. The signal from LO laser can be expressed as [16]:

$$E_{LO}(t) = \frac{1}{\sqrt{2}}\sqrt{P}_{LO}\exp[j(2\pi f_{LO} t + \varphi_{LO}(t))] \tag{5}$$

where P_{LO} means LO laser optical power and that split into two orthogonal polarized signals by a PBS. f_{LO} and φ_{LO} represent the frequency and phase of LO laser, correspondingly. After polarization, the balanced PD output is given as [16]:

$$X(t) = R\sqrt{2P}_{LO}P_x(t)\sin[2\pi\Delta f t + \varphi_x(t) - \varphi_{LO}] \tag{6}$$

where $\Delta f = f_c - f_{LO}$ means frequency offset of LO and carrier lasers. R is the responsivity of balanced PD. Thus, I and Q sub-bands per wavelength are given as:

$$XI(t) = \frac{1}{2}R\sqrt{2P}_{LO}P_x(t)\cos[\varphi_x(t) - \varphi_{LO}] \tag{7}$$

and

$$XQ(t) = \frac{1}{2}R\sqrt{2P}_{LO}P_x(t)\sin[\varphi_x(t) - \varphi_{LO}] \tag{8}$$

Similarly, for Y polarization, I and Q sub-bands per wavelength are given as:

$$YI(t) = \frac{1}{2}R\sqrt{2P}_{LO}P_Y(t)\cos[\varphi_Y(t) - \varphi_{LO}] \tag{9}$$

and

$$YQ(t) = \frac{1}{2}R\sqrt{2P}_{LO}P_Y(t)\sin[\varphi_Y(t) - \varphi_{LO}] \tag{10}$$

where P_Y and φ_Y present mean modulated amplitude and phase for Y polarization.

FIGURE 1(d) illustrates the fiber distribution architecture of the proposed system. The bidirectional fiber leaving the OLT is usually split, utilizing a 1:8 bidirectional power splitter for eight ONUs. Each ONU incorporates pre-assigned downlink and unlink wavelengths in the system. Again, 1:n splitter is used in each ONU to transmit the data traffic to 'n' number of users. Here, the splitter ranges from 1:8 to 1:64.

Although, in practical PONs, each ONU gets allocated a time-slot in which it is permitted to transfer its data packets. By guarded synchronization of these time-slots, packets collisions are avoided. As in PON, each ONU possess its own transmission range and thus its own delay. Accordingly due to the distinct range the path as well as exhibit distinct losses. Therefore, at OLT the receiver has to deal with packets coming with distinct intensity levels. It involves a fast clock extraction as well as adaption of the threshold level per packet. This is not a simple process, but can be implemented in hybrid TWDM-DFMA PON at low cost, long-reach and aggregate high data-rate. Moreover, achieving proper timing synchronisation among ONUs engaging the same signal spectral region is important for the PON operation. In hybrid TWDM-DFMA PON, after the digital filtering operation, for each TWDM signal, the digital-domain time delay operation in DFMA's digital filter is performed. Digital-domain time delay process is to synchronise distinct ONUs [1], [6].

Also, in conventional PONs, the asynchronous clock schemes are employed, which results in the sampling frequency offset (SFO) DAC as well as ADC. The SFO effects induce inter-symbol interference, inter-carrier interference and phase rotation. These effects causes severely degrade the receiver's performance in asynchronous discrete multi-tone systems. Out of several methods used in [5], [6], [7], [8], [9], [10], [11], [12], [13], and [14], to effectively compensate SFO, a hybrid TWDM-DFMA PON is the most effective approach [1], [6].

Table 1 defines the various parameters used in the proposed PON system.

TABLE 1. Parameters used.

Parameter	Value
Downlink wavelengths	1596-1601.6nm
Uplink wavelengths	1527-1532.6nm
Channel spacing	0.8nm
Downlink optical input power	10dB
Uplink optical input power	0dB
MZM modulation bandwidth	20GHz
DAC/AC sample rate	12GS/s
Up-sampling factor	8
Digital filter length	64
SMF length	10-150km
SMF attenuation	0.2dB/km
SMF dispersion slope	$0.08ps/nm^2/km$
SMF dispersion	17ps/nm/km
Reference wavelength	1550nm
PD thermal noise	10^{-22} W/Hz
PD responsivity	0.9A/W
PD shot noise	ON

FIGURE 2 presents the flowchart of the hybrid TWDM-DFMA PON design. After designing the proposed system for eight downlink and eight uplink channels, the performance of the system is calculated for received optical power (ROP), signal to noise ratio (SNR) and optical signal to noise ratio (OSNR) at BER limit of 10^{-3}. The maximum fiber length and highest number of connected ONUs are calculated at BER limit along with energy consumption in the proposed system.

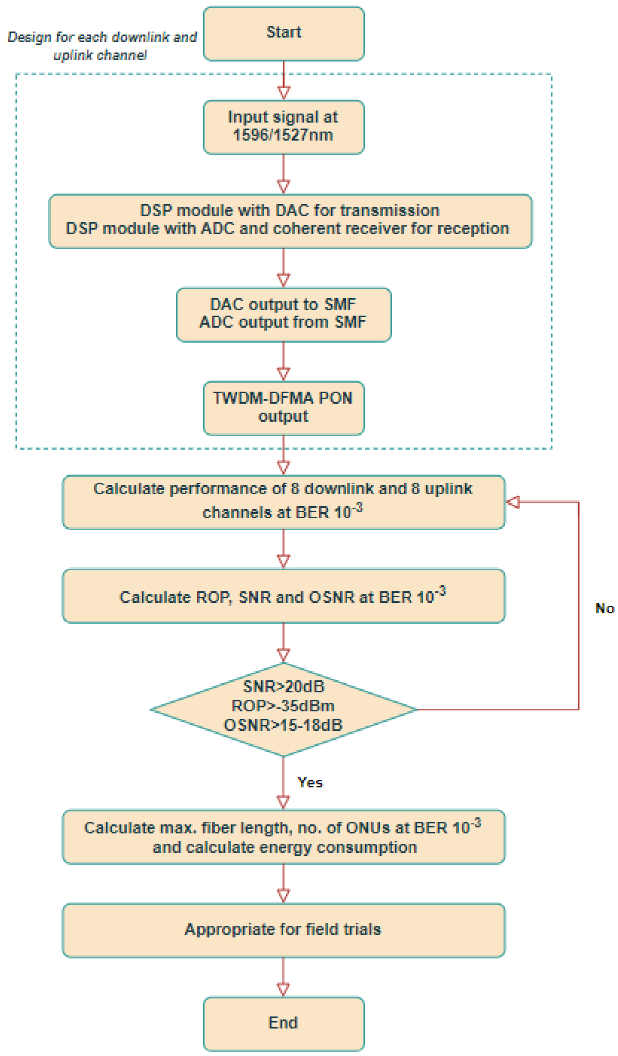

FIGURE 2. Flowchart of the hybrid TWDM-DFMA PON design.

III. RESULTS AND DISCUSSION

In this section, the results gotten from the proposed bidirectional eight channels hybrid TWDM-DFMA PON system design are depicted and discussed for both downstream as well as upstream transmission considering 10^{-3} BER threshold, in OptiSystemV.19 software.

FIGURE 3 illustrates the BER performance of hybrid TWDM-DFMA PON system at 25Gbps per channel data rate over 50km fiber distance for four downlink and four uplink channels. The BER limit of 10^{-3} by dashed line is as well displayed. It is depicted that CH1 (operating at 1596nm for downlink and 1527nm for uplink) in the system offers best performance followed by CH3, CH5 and CH7 respectively. The minimum acceptable received optical power of <-19, <-19, −15 and -12dBm for CH1, CH3, CH5 and CH7 respectively, is achieved at BER limit in uplink transmission. Moreover, the minimum received power for CH1, CH3, CH5 and CH7 in downlink transmission is −14, −13.5, −12 and −11dBm respectively. Besides this, the measured eye diagrams at −13dBm received power for CH1 in both in downlink as well as uplink direction, illustrates the successful transmission of data traffic in the presence of channels noise and interference. It is because of channel fading which results in unwanted power leakage among eight channels, especially in downlink.

Further, the system performance can be measured in terms of SNR, gain (G) and noise figure (NF). SNR is the ratio of amplitude of the required signal to the amplitude of noise signals at BER limit of 10^{-3}. SNR in terms of BER is written as [17]:

$$BER = \frac{1}{2} erfc\left(\sqrt{\frac{SNR}{8}}\right) \tag{11}$$

where *erfc* means complementary error function. Since BER performance is proportional to $erfc\sqrt{SNR}$, thus higher SNR value (in dB) results in better system performance. Furthermore, SNR value deterioration between the input and the output of the received signal represented as NF.

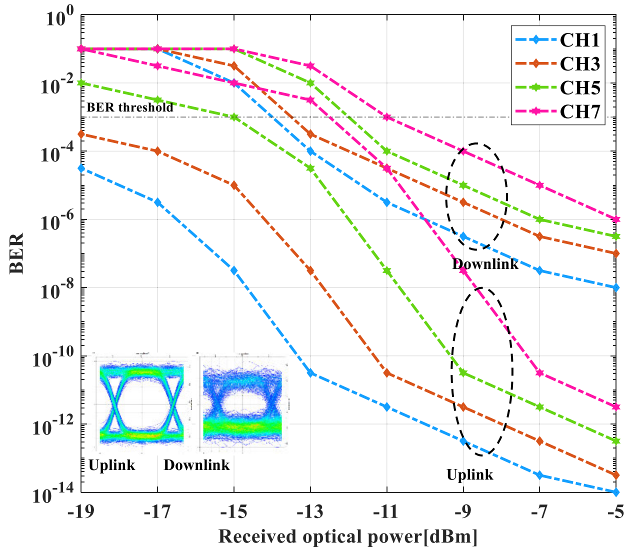

FIGURE 3. Calculated BER vs. received optical power at symmetric 25Gbps data rate per channel over 50km transmission length for four channels (CH1, CH3, CH5 and CH7) in both downlink as well as uplink transmission direction in the system. Insets: corresponding eye patterns at −13dBm received power for CH1 in downlink and uplink transmission.

It is represented as:

$$NoiseFigure\ (NF) = 10log_{10}\left(\frac{SNR_i}{SNR_o}\right) \text{dB} \quad (12)$$

where output and input SNR are represented as SNR_i and SNR_o respectively. Lower the value of NF, better the system performance. Also, system gain is defined as the ratio of change in input to change in output. It is expressed as:

$$Gain = 10log_{10}\left(\frac{OutputPower(P_o)}{InputPower(P_i)}\right) \text{dB} \quad (13)$$

Higher the gain, more susceptible the signal is to channel interference and obstruction. Tables 2 and 3 depict the performance measurement of proposed work for downlink and uplink transmission respectively, for different channels.

TABLE 2. Performance analysis of TWDM-DFMA PON for downlink transmission @ 10^{-3} BER.

Channel (nm)	SNR (dB)	Input power (dB)	Gain (dB)	Noise Figure (dB)
CH1 (1596)	99	10	-2.3	2.3
CH2 (1596.8)	98	10	-2.6	2.5
CH3 (1597.6)	96	10	-2.8	2.6
CH4 (1598.4)	95	10	-3.0	2.8
CH5 (1599.2)	93	10	-3.4	2.9
CH6 (1600)	88	10	-3.7	3.1
CH7 (1600.8)	83	10	-3.9	3.4
CH8 (1601.6)	80	10	-4.1	3.6

From Tables, it is observed that uplink channels perform better than downlink in terms of SNR, gain and noise figure. The better performance in the uplink is due to the use of a coherent receiver for uplink transmission in the proposed system. It is also shown that CH1 shows better performance than other channels in both downlink and uplink direction.

TABLE 3. Performance analysis of TWDM-DFMA PON for unlink transmission @ 10^{-3} BER.

Channel (nm)	SNR (dB)	Input power (dB)	Gain (dB)	Noise Figure (dB)
CH1 (1527)	100	0	-2.0	2.0
CH2 (1527.8)	98	0	-2.3	2.1
CH3 (1528.6)	99	0	-2.5	2.2
CH4 (1529.4)	97	0	-2.9	2.3
CH5 (1530.2)	96	0	-3.1	2.4
CH6 (1531)	90	0	-3.2	2.6
CH7 (1531.8)	87	0	-3.3	2.8
CH8 (1532.6)	85	0	-3.5	3.0

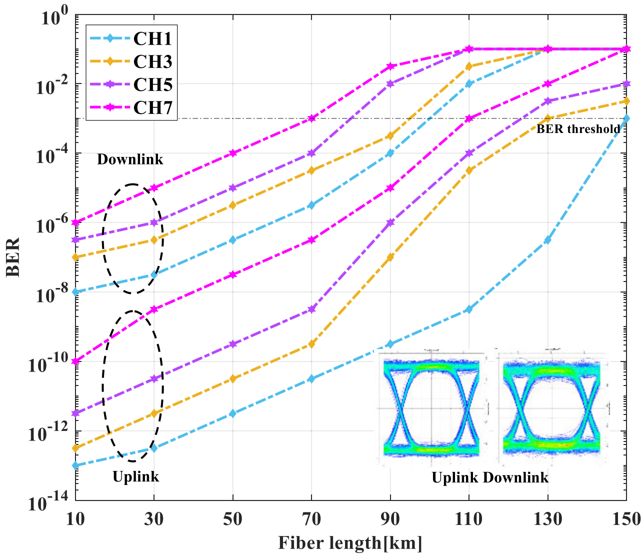

FIGURE 4. Calculated BER vs. fiber length at symmetric 25Gbps data rate for four channels (CH1, CH3, CH5 and CH7) in both downlink and uplink transmission of the system. Insets: corresponding eye patterns over 100km fiber length and at 10dBm power for CH1 in both downlink as well as uplink transmission.

FIGURE 4 shows the influence of different downlink and uplink channels (CH1, CH3, CH5 and CH7) and varied fiber transmission lengths on BER in the hybrid TWDM-DFMA PON system at 25Gbps per channel data rate. It is distinguished that with the fiber length increased, the BER performance is becoming worse for both transmission directions. The system performance of CH1 is better than other channels over long distance for uplink transmission followed by downlink, which is caused by more channels crosstalk in downlink transmission channels. The maximum fiber distance obtained for CH1, CH3, CH5 and CH7 is 150, 130, 120 and 110km respectively, for uplink transmission at acceptable BER threshold of 10^{-3}. Also, the faithful transmission distance in downlink transmission at BER threshold for CH1, CH3, CH5 and CH7 is 100, 95, 80 and 70km respectively.

Besides this, FIGURE 4 presents the eye diagrams for CH1 in downlink and uplink directions over 100km fiber length at

10dBm input power. It is seen that channel distortion is less in uplink channel than downlink channel considering fiber non-linearities, noise and interferences. Also, it is basically occurs because the proposed design suffers the strongest undesirable cross-talk among distinct downlink channels than uplink ones.

Tables 4 and 5 present and validate the performance measurement of proposed work for downlink and uplink transmission, correspondingly for diverse fiber lengths.

TABLE 4. Performance analysis of TWDM-DFMA PON for downlink transmission @ 10^{-3} BER for CH1.

Length (km)	SNR (dB)	Received power (dBm)	Gain (dB)	Noise Figure (dB)
10	97	0.84	-2.1	2
50	94	0.80	-2.6	2.5
90	91	0.77	-3.1	2.8
110	86	0.73	-3.6	3.2
150	81	0.69	-3.8	3.5

TABLE 5. Performance analysis of TWDM-DFMA PON for unlinktransmission @ 10^{-3} BER for CH1.

Length (km)	SNR (dB)	Received power (dBm)	Gain (dB)	Noise Figure (dB)
10	108	0.89	-1.1	1.5
50	106	0.84	-1.6	1.7
90	102	0.80	-2.0	1.9
110	98	0.77	-2.5	2.2
150	92	0.72	-2.7	2.5

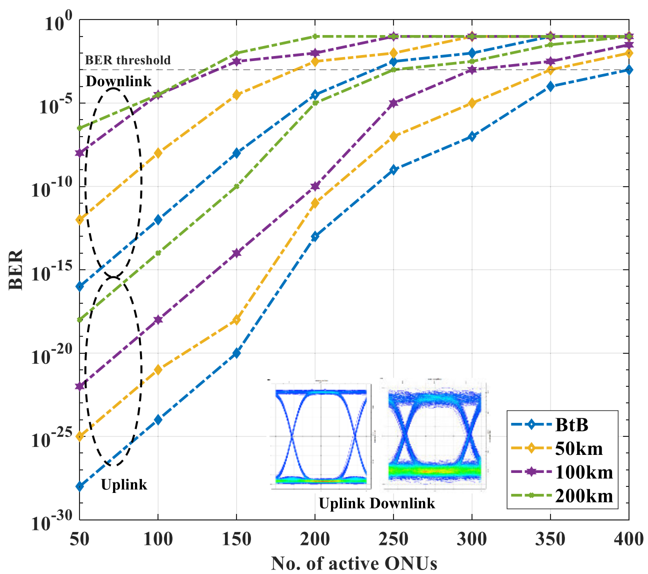

FIGURE 5. Calculated BER vs. number of active ONUs at symmetric 25Gbps data rate for BtB, 50km, 100km and 200km fiber ranges in both downlink and uplink transmission of the system for CH1. Insets: corresponding eye patterns for 250 active ONUs for CH1 through BtB downlink and uplink transmission links.

FIGURE 5 presents the relationship between number of active ONUs and the BER of the symmetric 8 × 25Gbps hybrid TWDM-DFMA PON for back-to-back, 50km, 100km and 200km SMF lengths in both downlink as well as uplink transmission channels. It is seen that the performance of the system diminishes with the increase in number of ONUs in terms of increase in respective BER. It is due to restricted received power by power combiners and power splitters for both downlink and uplink channels as well as fiber interference and non-linearities. To obtain the performance of distinct ONUs, the back-to-back (BtB), the BER performance of CH1 at downstream and upstream transmitters is measured. For BtB channels in downlink as well as uplink transmission, the highest number of ONUs offered by the proposed system are 240 and 400 respectively. While, the highest number of active ONUs supported over 50, 100 and 200km fiber ranges are 190, 140 and 120 respectively, in downlink transmission at BER threshold. Also, the number of active ONUs can be increased upto 350, 300 and 250 over 50, 100 and 200km fiber length for uplink transmission in the system. The eye diagrams are obtained by BER analyzer for CH1 through BtB link for uplink and downlink transmission.

The clear and open eye-diagrams have been measured for upstream CH1 which support 250 number of ONUs in the system. Tables 6 and 7 illustrate the performance measurement of proposed work for downlink and uplink transmission respectively, for different no. of ONUs. Besides this, Tables 8 and 9 present the performance measurement of the system supporting 50 ONUs at BER limit for downlink and uplink transmission respectively.

TABLE 6. Performance analysis of TWDM-DFMA PON for downlink transmission @ 10^{-3} BER for CH1.

No. of ONUs	SNR (dB)	Received power (dBm)	Gain (dB)	Noise Figure (dB)
50	90	0.77	-3	2.8
150	88	0.74	-3.2	3.0
250	84	0.71	-3.5	3.3
350	80	0.65	-3.9	3.7

TABLE 7. Performance analysis of TWDM-DFMA PON for unlink transmission @ 10^{-3} BER for CH1.

No. of ONUs	SNR (dB)	Received power (dBm)	Gain (dB)	Noise Figure (dB)
50	95	0.87	-2.7	2.2
150	92	0.83	-3.0	2.5
250	88	0.77	-3.2	2.9
350	84	0.70	-3.5	3.1

FIGURE 6 illustrates the BER performance of system at NRZ modulation at bit rate of 25Gbps per channel over 100km SMF for single downlink and single uplink channels with and without DFMA. It is noted that channels incorporating DFMA in the system offers better performance than without DFMA. The minimum received power for uplink channel with and without using DFMA is −16 and −12dBm

TABLE 8. Performance analysis of TWDM-DFMA PON for downlink transmission @ 10^{-3} BER for 50 no. of ONUs.

Channel (nm)	SNR (dB)	Received power (dBm)	Gain (dB)	Noise Figure (dB)
CH1 (1596)	90	0.77	-3	2.8
CH2 (1596.8)	88	0.80	-3.6	3.0
CH3 (1597.6)	86	0.83	-3.8	3.2
CH4 (1598.4)	85	0.86	-4.0	3.5
CH5 (1599.2)	83	0.89	-4.4	3.7
CH6 (1600)	78	0.92	-4.7	4.0
CH7 (1600.8)	73	0.95	-4.9	4.2
CH8 (1601.6)	70	0.99	-5.1	4.4

TABLE 9. Performance analysis of TWDM-DFMA PON for unlink transmission @ 10^{-3} BER for 50 no. of ONUs.

Channel (nm)	SNR (dB)	Received power (dBm)	Gain (dB)	Noise Figure (dB)
CH1 (1527)	95	0.87	-2.7	2.2
CH2 (1527.8)	92	0.89	-2.9	2.4
CH3 (1528.6)	90	0.91	-3.1	2.6
CH4 (1529.4)	88	0.93	-3.3	2.8
CH5 (1530.2)	86	0.95	-3.7	3.0
CH6 (1531)	84	0.97	-3.9	3.2
CH7 (1531.8)	82	0.99	-4.2	3.5
CH8 (1532.6)	80	1.02	-4.4	3.7

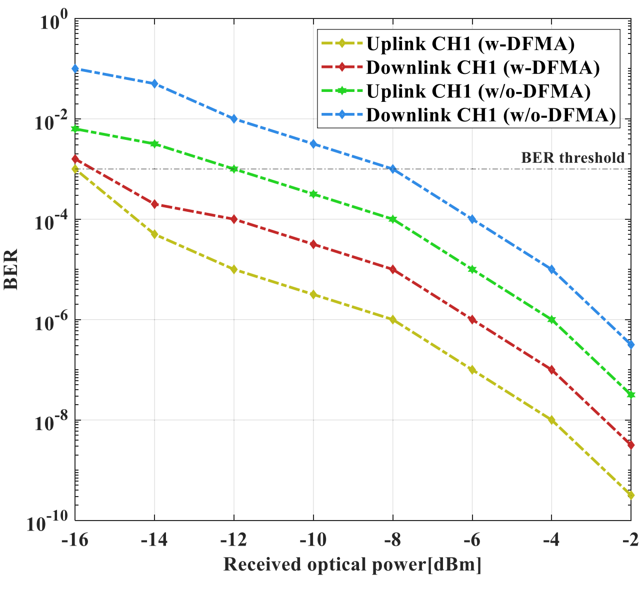

FIGURE 6. Calculated BER vs. received optical power at symmetric 25Gbps data rate over 100km transmission length for single channel in both downlink and uplink transmission with and without DFMA.

respectively, at BER limit. While for downlink channels provides received power of −15.5dBm with DFMA and −8dBm without DFMA. Above all, the system with DFMA can obtain the 4dB uplink and 7.5dB downlink power budgets than the case without DFMA. This power budget is basically provided by the multiple access interference among different channels.

This is due to the reason that proposed hybrid TWDM-PON with DFMA implements shaping filters at OLT with their respective matching filter at ONUs and thus the distinct channels are modelled dynamically to share the SMF. Besides this, the coherent receiver used in the proposed system offers the high flexibility and scalability from Gbps to Tbps per wavelength at a low cost per bit. It also compensates polarization mode and chromatic dispersion using DSP module [9].

TABLE 10. Performance analysis of TWDM-DFMA PON for downlink transmission @ 10^{-3} BER.

Channel (nm)	ROP (dBm) [w/o-DFMA]	ROP (dBm) [w-DFMA]
CH1 (1596)	-8	-15
CH2 (1596.8)	-7	-14
CH3 (1597.6)	-6	-14
CH4 (1598.4)	-6	-13
CH5 (1599.2)	-5	-13
CH6 (1600)	-5	-12
CH7 (1600.8)	-4	-12
CH8 (1601.6)	-4	-12

TABLE 11. Performance analysis of TWDM-DFMA PON for uplink transmission @ 10^{-3} BER.

Channel	ROP (dBm) [w/o-DFMA]	ROP (dBm) [w-DFMA]
CH1 (1527)	-12	-16
CH2 (1527.8)	-12	-15
CH3 (1528.6)	-11	-15
CH4 (1529.4)	-11	-14
CH5 (1530.2)	-10	-13
CH6 (1531)	-10	-13
CH7 (1531.8)	-10	-13
CH8 (1532.6)	-9	-13

From Tables 10 and 11, it is observed that uplink channels perform better than downlink in terms of SNR, gain and noise figure.

FIGURE 7 presents the OSNR performance w.r.t. uplink and downlink channels over 100km transmission distance at 25Gbps per channel data rate.

It is depicted that that OSNR values minimized linearly with increase in channels for both uplink and downlink transmission channels. It causes owing to the existence of fiber dispersion, attenuation, noise, non-linearities as well as channels interference. As compared to TWDM-PON, the proposed hybrid TWDM-DFMA PON offers significant advantages like enhanced upstream transmission performance, robustness against channel interference, and no extra DSP required reducing the inter-carrier interference effects distinct upstream ONU signals. Also, hybrid TWDM-DFMA PON has superb upstream performance robustness opposed to channel interferences, transmission system channel interferences and digital filter characteristic variations.

The highest obtained OSNR for uplink one, three, five and seven channels is 91, 85, 78 and 75dB respectively at BER limit of 10^{-3}. Moreover, for downlink transmission

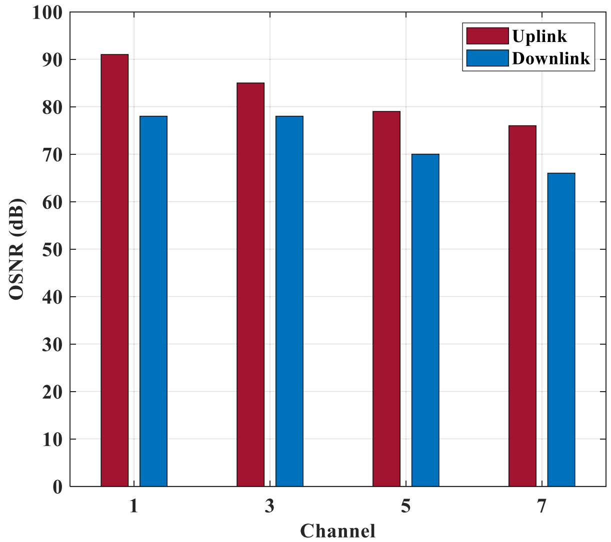

FIGURE 7. OSNR performance of downlink and uplink channels in proposed PON using DFMA.

offer maximum OSNR of 79dB for single, 78dB for three, 70dB for five and 65dB for seven channels. Therefore, the proposed TWDM-DFMA PON offers long-reach and high transmission rate successfully.

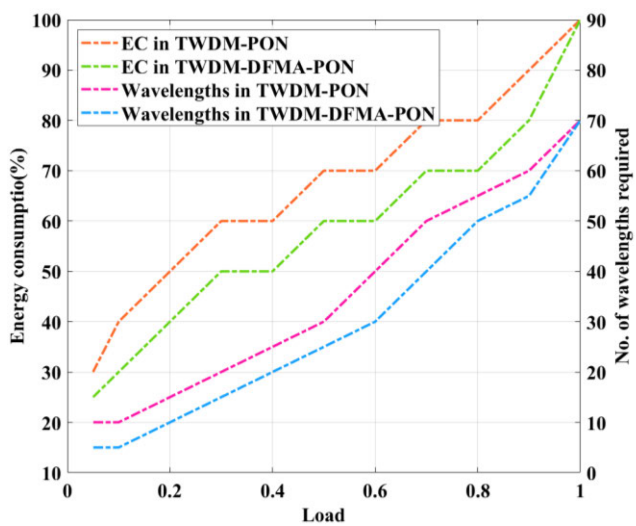

FIGURE 8. Calculated energy consumption and number of wavelengths required in TWDM-PON and hybrid TWDM-DFMA PON w.r.t. load at RN.

FIGURE 8 illustrates the energy consumption (EC) at OLT when the ONUs are clustered at the same wavelength as per the distances still fulfilling the transmission rate of the users. For that, the ONUs are meant to be distributed evenly between 50 and 100km. Also, when all transceivers are on, the 100% energy is consumed by the system. From figure it is depicted that however TWDM-PON approach already saves about 70% energy at low transmission rate. But with hybrid TWDM-DFMA PON approach the energy consumption is again reduced to 25% i.e., 75% energy saving at the OLT. Since the power for cooling is generally the two times of the system power applied. Thus, this saving also save power at OLT for cooling as well as minimize operational cost of the network provider. Moreover, it is shown that energy consumption rises as the number of wavelengths used at the OLT increases. Out of both systems, the proposed system operating with less number of wavelengths offers better performance in terms of more energy saving at high data rate operating [18]. Again, Table 12 presents the comparative performance analysis of the proposed work with other existing work in terms of data rate and transmission distance.

TABLE 12. Comparative performance of the designed hybrid TWDM-DFMA PON with existing systems.

Reference	Maximum data rate per wavelength (Gbps)	Maximum transmission distance (km)
[3]	0.625	26
[9]	0.7	26
[4]	0.75	26.5
[1]	4.7	25
[13]	10	50
[7]	13.125	25
[14]	15	25
[6]	30	25
[8]	32.5	26
[11]	50	26
[12]	101.6	25
Proposed work	25	150

It is noted that the hybrid TWDM-DFMA PON offers maximum aggregate data rate of 200Gbps (=8 × 25Gbps) and transmission distance of 150km.

IV. CONCLUSION

An 8 × 25Gbps hybrid TWDM-DFMA PON system has been designed and investigated in OptiSystem simulation software. The system performs better for uplink transmission than downlink transmission. At acceptable BER, the minimum power received is -19dBm for uplink channel at 1527nm and –14dBm for downlink channel at 1596nm over a 50km transmission range. The transmission range can be extended upto 150km and 100km for uplink and downlink transmission, respectively. Also, the highest number of supported ONUs by proposed system is 250 in uplink and 120 in downlink transmission. Additionally, the proposed TWDM-PON system with DFMA can enhance the uplink and downlink high power budget of 4dB in comparison to the system without DFMA, with a maximum OSNR of 91dB in uplink and 79dB OSNR in downlink. It also saves more energy in the system as compared to other systems. Moreover, compared with the traditional PON systems, the TWDM-DFMA PON is more flexible and energy efficient, offering a high data rate as well as a long transmission range.

Thus, in future, the proposed design may be a significant solution for high-speed, long-reach and cost-sensitive low latency 5G based networks. It also has much potential for realizing future SDN-cloud access networks [4]. Moreover, it offers superb robustness against transmission impairments in fiber, considerable channel interference reductions and unsophisticated backscattering as well as channel fading effects [12].

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MEET KUMARI received the B.Tech. degree in electronics and communication engineering from Guru Nanak Dev University, Regional Campus Gurdaspur, Punjab, India, the M.Tech. degree in electronics and communication engineering from Guru Nanak Dev University, Regional Campus Jalandhar, Punjab, and the Ph.D. degree in electronics and communication engineering from Punjabi University, Patiala, India, in 2021. Currently, she is an Assistant Professor with Chandigarh University, Mohali, Punjab. She has published many SCI and Scopus papers/book chapters in reputed international journals/conferences. Her research interests include optical communication, green communication, next generation networks, and wireless sensor networks.

VIVEK ARYA received the M.Tech. degree (Hons.) in electronics and communication engineering. He qualified the UGC NET exam. He is currently an Assistant Professor with the Department of Electronics and Communication Engineering, Faculty of Engineering and Technology, Gurukula Kangri (Deemed to be University), Haridwar, India. His research interests include digital image processing, antennas, optical communication, and biosensors. He has patented many inventions at national level and at international level. He has published many SCI and Scopus papers/book chapters in reputed international journals/conferences. He also serving as a reviewer in many journals for international repute, such as Wiley, WSEAS Transactions, and IGI Global & Springer.

HAMZA MOHAMMED RIDHA AL-KHAFAJI (Senior Member, IEEE) received the B.Sc. degree in electronic and communications engineering and the M.Sc. degree in modern communications engineering from Nahrain University, Baghdad, Iraq, in 2004 and 2007, respectively, and the Ph.D. degree in communication engineering from Universiti Malaysia Perlis, in 2014. He has five years working experience as a Senior BSS Engineer with Huawei Technologies and Omnnea Wireless Telecom, Iraq, from 2006 to 2010. After that, he completed one year postdoctoral research with Universiti Teknologi Malaysia. He has been a Faculty Member with Al-Mustaqbal University, Iraq, since September 2015. He has published more than 80 articles, mainly on optical fiber communication systems, next generation wireless networks, the Internet of Things, and optimization algorithms. He has served as an academic editor and a reviewer in many international journals and conferences. He is a Senior Member of IACSIT and IEU and a member of IEICE, ACM, IAENG, SDIWC, ICSES, IASED, APSIPA, and QEAAS Society.