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Fifth generation IoT technology incorporated hybrid OCDMA-WDM passive optical network employing RGB LEDs visible light communication system

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A light internet of things (LIoT) based hybrid 10/2.5 Gbps bidirectional wavelength division multiplexing (WDM) together with optical code division multiple access passive optical network (OCDMA-PON) incorporating red-green-blue light emitting diodes (LEDs) visible light communication (VLC) is proposed and investigated. Simulation results indicate that using blue LED, hybrid 10 km fiber and 2.2 m VLC range is achieved with receiver sensitivity of -9 dBm. Also, the proposed system utilizing modified new zero cross-correlation (MNZCC) code offers a faithful transmission distance of 70 km fiber and 10 m VLC with high optical signal to noise ratio of 101.11 dB for 39 users than others codes and existing designs.

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Keywords: OCDMA, PON, WDM, VLC

1. Introduction

In past years, various favorable perceptions and technologies on cordless systems were presented and extensively studied. An aspiring paradigm of internet of things (IoT) spreading the province of internet to allow wireless networking to objects over internet framework. Wireless inter-networks were originally composed to allow connectivity to users, though networks and users' demands developed largely, bringing too wireless links to computers, machines, sensors as well as vehicles. An IoT can be considered as the extreme connectivity issue, where essentially whatever can be a wireless network node of worldwide coverage. Theoretically, any target can be interconnected, small else large, mobile or stationary and placed in every possible circumstance. As communication and energy demands very wide-ranging, depend on the services & applications. In this, an IoT is a final step for whole wireless interconnected world. An enormous IoT market, values in trillion dollars has been predicted by Cisco. Since IoT usually feats sensing, revelations foresee wide demands for IoT sensors and trillions of sensors nodes are likely to be deployed throughout. Information can be sent to or received from each and every joined IoT points. The extent of this technique could easily need several orders of magnitude of wireless links more than current's connections operating principally subscribers [1].

Considering extensive number and different kinds of targets to be access networked, attaining higher energy as well as cost saving along with efficient usage of the communication media becomes essential for IoT. These technical issues and node's energy autonomy, privacy and security require to be addressed to meet IoT provisions. Recent IoT solutions, utilizing radio connections, strive to accomplish some of these needs. Optical wireless communications, especially visible light communication (VLC), allow a feasible replacement to radio connection for limited communication. A VLC communication technique has developed expeditiously over the past ten years, and nowadays it is a worldwide developed technology. This technology using light emitting diodes (LEDs) initiated in Japan in 2000, with the visible light communication consortium acting a key early role [1,2]. Little while ago, Z. Wang et al. proposed and experimentally demonstrated a 2×2 multiple input multiple output VLC using joint IQ independent component over a 1.3 m range at 750 Mbps data rate [3]. M. A. de Oliveira et al. implemented a red-green-blue (RGB) based VLC system for fifth generation new-radio. The investigated results indicate that the proposed system can be realized successfully at 1.92 Gbps over a transmission range of 2 m [4]. F. Ahmad et al. experimentally implemented a laser based VLC system over a 300 cm transmission distance at 1.5 Gbps data rate [5]. J. T. Wu et al. proposed and demonstrated the LED-based 1Mbps VLC system using the solar cell as a receiver and pre-distortion Manchester coding over 150 cm wireless range [6]. L.-Y. Wei et al. realized the VLC based wireless network full-duplex system at 2.3 Tbps over 1.5 m wireless range to provide both lighting and communications for 400 VLC users [7]. S. Chaudhary et al. experimentally demonstrated the a non-return to zero (NRZ) on-off keying (OOK) modulation basics VLC system using post-amplification approach at 62.5 Mbps transmission rate over 6m wireless range. [8]. Also, T.-T. Tsai et al. demonstrated a sensor based VLC system using spatial modulation and under-sample modulation. The results indicates that throughput of 720 bps can be obtained in VLC system using 4-white LEDs over a 100 m range [9]. K. Sindhubala et al. proposed and analysed 20 Kbps return to zero OOK VLC system over 20 m wireless range under the impact of optical background noise [10]. VLC provides unique benefits like unlimited license-free bandwidth, security, privacy, mobility and many others as the light remains limited in an active room. The standard IoT's low transmission rate requirements results in low-power and simple outcomes for optical networks. The same optical link used to light the room and transmit wirelessly data can be utilized by an IoT object to collect energy to boost all systems in the current years [11]. Q. Chen et al. demonstrated an orthogonal frequency division multiplexing (OFDM) VLC system employing joint pre-processing technique to improve the performance of bit error rate (BER) of the system at 150 Mbps data rate over an 80 cm distance successfully [12]. J. Lian et al. proposed an indoor multi-VLC system employing OFDM over a 5 m range at 350 Mbps data rate [13]. G. Miriyala et al. demonstrated a nonlinear modelled asymmetrically clipped direct current biased OFDM for VLC system over a 2 m distance at 8 Mbps [14]. M. T. Rahman et al. proposed coarse wavelength division multiplexing VLC system with multiple LEDs the hybrid functionalities onboard [1]. Various multiple access techniques, like time and wavelength division multiplexing (TDMA), wavelength division multiplexing (WDM), optical code division multiple access (OCDMA), OFDM etc., are utilized with VLC having distinct monochromatic colors to enhance the transmission rate. The simulative results present that system can accomplish a high 3.2 Gbps and 7.2 Gbps transmission rate for 10 and 20 links respectively over a 3 m range [15]. C. W. Chow et al. demonstrated the 1MHz-6.14 Mbps LED-based OFDM-VLC system over a 2 m wireless range [16]. H. Li et al. reported the 682 Mbps white LED-based 16 level quadrature amplitude modulation (16QAM)-OFDM-VLC system over 1m of VLC range [17]. N. Chi et al. proposed and experimentally demonstrated a RGB LED based 2×1.6 Gbps 16QAM-OFDM-VLC system over 1.1 m wireless distance [18]. X. Li et al. reported 625 Mbps multi-channel RGB LED-based uplink VLC system using TDM multiplexing scheme as well as OOK modulation at 6.2 m VLC range [19]. The present PON technologies are facing issues such as low bit rate, low capacity and high cost because of the use of the TDMA multiplexing technique which has limited time slots, inefficient use of scalability and limited capacity for end-users. While, OFDM-PON lacks in complex receivers, optical beat noise, frequency offset and high cost.

Considering the favors of VLC system, a combination of WDM and VLC is essential for 5G for building the corresponding the strengths. The recent studies on WDM-VLC have been performed for analyzing the performance of hybrid WDM-VLC systems [20]. J. Zhang et al. experimentally demonstrated the OFDM based WDM-VLC system using RGB LED and channel estimation technique based on inter-block data pre-coding and superimposed pilots over wireless 0.8 m range at 1.87 Gbps and 2 m VLC link at 1.57 Gbps transmission rate. [21]. Lu Cui et al. reported a LED based VLC-WDM system using OOK modulation for 12 channels over a transmission distance of 30 cm at 5.1 Gbps data rate [22]. G. C. Mandal et al. demonstrated via experimental a bidirectional WDM hybrid VLC-fiber based on reflective semiconductor optical amplifier and self-injection locked quantum dash laser over a 50 km fiber distance. The results show that data can be faithfully transmitted at 10 Gbps over a 50 km fiber length and 10 m VLC range at acceptable BER of 10^{-9} [23]. At our utmost knowledge, most of the relevant WDM-VLC researchers have primarily focused on the model simulation. The most of the existing WDM-VLC transmission investigation lacks in to fulfill the requirements of high capacity and integration simultaneously. Therefore, a high-speed WDM-OCDMA system employing VLC has been utilized [24].

Moreover, for better security and spectral efficiency, OCDMA passive optical network (PON) can be extensively employed in WDM-VLC system as a next generation fiber-to-the-x applications as comparatively expensive WDM components as well as restrictions of given wavelength prevent the extensive WDM-PON deployment. OCDMA provides network management, asynchronous data transfer for ease of control, enables managers to route applications with using complex multiplexers (MUXs) and demultiplexers (DEMUXs), suitability with exploding traffic networks and high quality of service [25,26]. In [27], A. E. A. Farghalproposed and analyzed the multi-core fiber based hybrid 16×1 Gbps space division multiplexing based spectral amplitude coded OCDMA PON system using balanced in-complete block design codes over 50km transmission distance. Results show that designed system allows reduction of a large number of fibers utilization. Moreover, the attractive benefits make OCDMA an advantageous technology for the next generation PONs (NG-PONs). Thus a combination of a WDM-VLC with OCDMA-PON for light internet of things (LIoT) applications can be a solution for NG-PON stage 3 (NG-PON3) for wired-wireless application [28]. Recently, C. Y. Chen et al. demonstrated the 500 Mbps hybrid VLC/WDM-PON system using phase modulation technique and injection-locked laser diode experimentally over 8 m wireless and 20 km wireless transmission distances [29]. J. He et al. experimentally demonstrated a WDM-PON employing carrier-less amplitude phase modulation to minimise the cost of WDM system along with visible laser light communication over a transmission distance of 20 km fiber and 4.5 m wireless distance at 10 Gbps data rate [30].

However the prior researchers of WDM-PON using VLC using wireless technologies are mostly focused on WDM and VLC parts as well as wireless communication media. In these demonstrations, except the few one [31], researchers don't pay attention to OCDMA codes with WDM-PON using VLC for LIoT applications as, some inescapable problems like multi-access interference (MAI) and phase-induced intensity noise (PIIN) especially in the transmission system can be reduces effectively using an optical OCDMA code [25]. Briefly, the hybrid OCDMA-WDM PON employing VLC is a superior system as it has ability to transfer continuous information signals even if one transmission link among fiber or VLC is damaged due to some environment restrains [32]. The main contributions of this work are as follows:

1. To propose and investigate a high-speed integrated OCDMA-WDM PON employing RGB LED basics VLC under influence of wireless link losses, noise, fibre nonlinearities, attenuation and dispersion through simulation and mathematical analysis.
2. To compare proposed work performance using distinct types of codes viz. flexible cross correlation (FCC), modified new zero-cross correlation (MN-ZCC), ZCC, hadamard, shift ZCC (SZCC) as well as modified quadratic congruence (MQC).
3. To compare proposed system performance with prior recent work.

The rest of the organized paper is- Sections 2 and 3 explain the proposed system design and its numerical analysis respectively. Results & discussion is reported in Section 4 then followed by Section 5, conclusion.

2. Proposed architecture

Fig. 1 presents the basic principle design of a hybrid WDM-OCDMA PON with RGB LED based VLC for more robust LIoT system where bidirectional communication i.e. downstream (DN) and upstream (UP) wired-wireless are utilized.

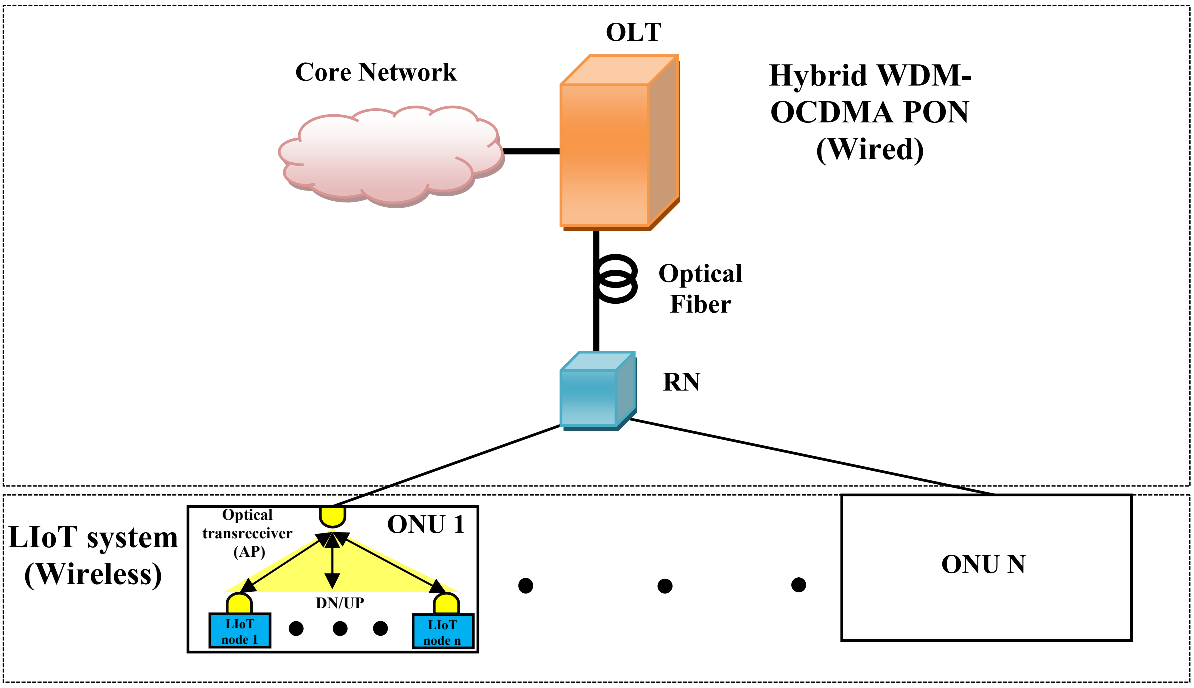


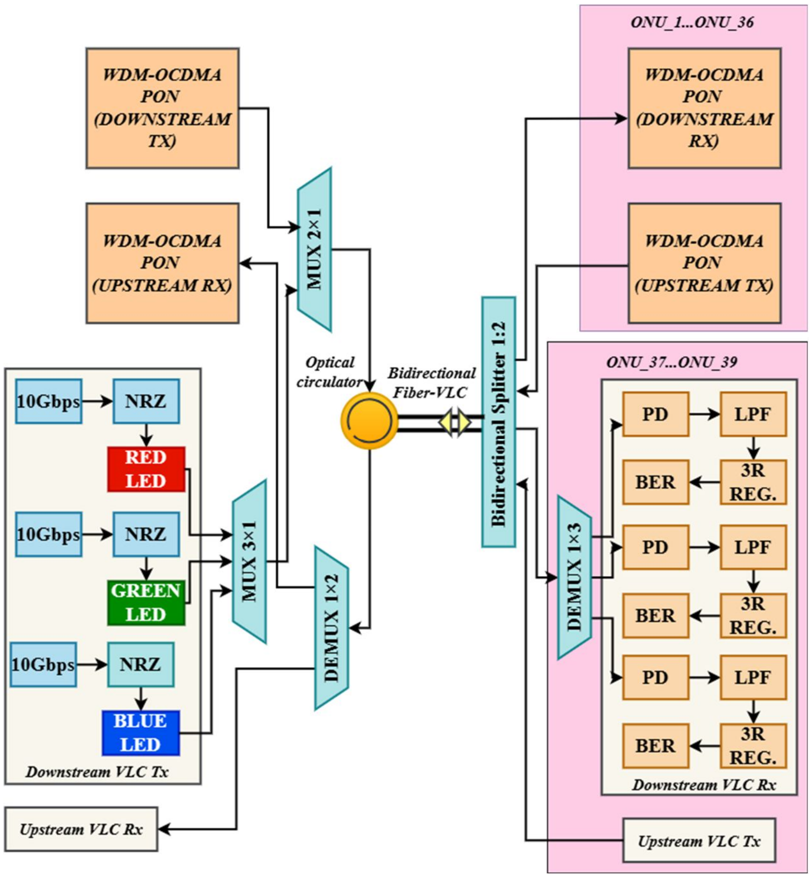
Fig. 1. Semantic diagram of an integrated OCDMA-WDM PON incorporating RGB LED based VLC system (color online)

The signal from optical line terminal (OLT) transferred via an optical cable accompanied through a remote node (RN) or optical distribution network (ODN) is incorporated to assign the coming signals to *N* no. various optical network units (ONUs). Again, fiber as well as VLC services are achieved by fiber cable followed by via wireless VLC links [33]. To support the LIoT in hybrid WDM-OCDMA PON employing VLC, a transceiver is utilized as an access point usually assembled on ceiling. Here, hotspot on ceiling overhead can be enlarged to reckon a lot of luminaries as well as associated optical nodes to offer room-wide range coverage. Each node will be associated to internet of light is exposed. LIoT is a complement to limited range IoT, though VLC. The wired-wireless linked energy-autonomous node functioning with hybrid WDM-OCDMA PON is definitely one significant advantages of this technique. The hybrid OCDMA-WDM PON together with VLC for LIoT can offers wired/wireless transmission with higher reliability as well as capacity backhaul sustaining to obtain long-reach communication requires for distinct services like residential, backhaul and business networks. It also minimises the wireless networks corns such as per-node low throughput, influence of unpredictable delays in transmission, inessential congestion and radio frequency serve environment conditions effectively and limited spectrum of RF. And one of challenge of an LIoT node i.e. higher energy transmission/node can be efficiently utilized PON with hybrid OCDMA-WDM multiplexing schemes. Thus the proposed system offers low energy required optical nodes than radio tags [1].

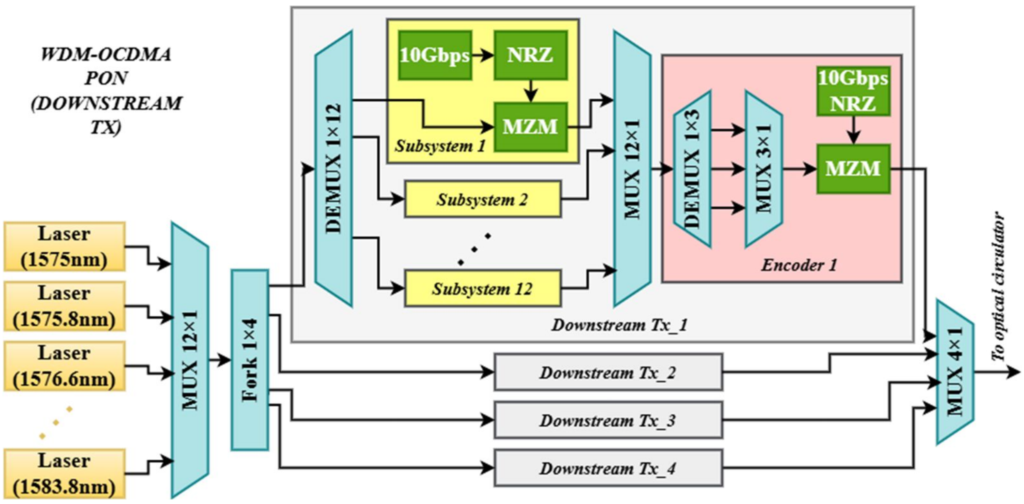
Here, RGB (red=625 nm, green=525 nm, blue=455 nm) LEDs based bidirectional VLC system is utilized to send data wireless in designed system. The benefit of using RGB to increase security of data as after combining of the light signals at particular %age produces white light. Also, the combination of RGB provides higher information rate upto 100 Gbps lower response as well as high bandwidth modulation as compared to a white LED. For VLC transmission, NRZ-OOK is used to carry data considering of 0s (i.e. positive) and 1s (i.e. negative) over line of sight (LOS) link [34,35].

2.1. System architecture

The systematic of full-duplex hybrid 12×3×10/2.5 Gbps OCDMA-WDM PON using MNZCC code as well as 3×10/2.5 Gbps VLC system for 39 users is indicated in Fig. 2(a). Here, OCDMA-WDM PON incorporates total thirty-six users and VLC system users comprise three users.



(a)



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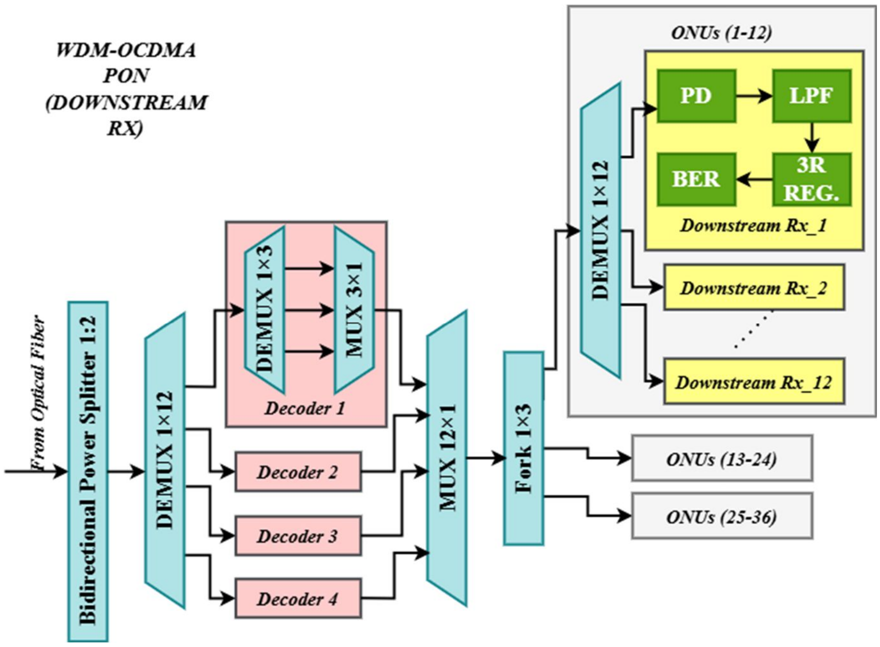

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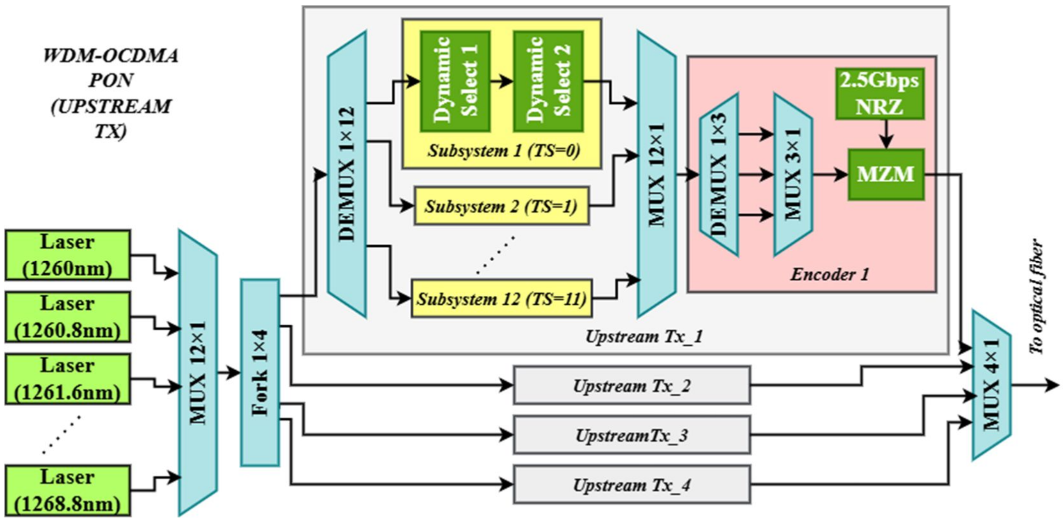
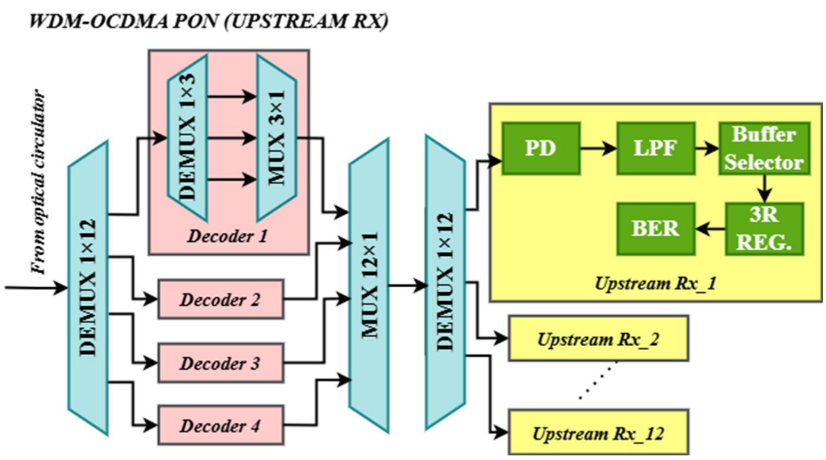


(d)



(e)

Fig. 2. (a) Conceptual diagram of full-duplex hybrid VLC-OCDMA-WDM PON utilizing MNZCC codes, (b) downstream transmitter section of OCDMA-WDM PON, (c) downstream receiver section of OCDMA-WDM PON, (d) upstream transmitter section of OCDMA-WDM PON and (e) upstream receiver section of OCDMA-WDM PON (color online)

2.1.1. Downlink design

In the proposed hybrid OCDMA-WDM PON, for two-way transmission, OLT as well as ONUs comprises *N* no. of tx/rx pairs depend on OCDMA code used i.e. for SZCC (*N*=6), ZCC (*N*=6), hadamard (*N*=4), MNZCC (*N*=12), FCC (*N*=10) as well as MQC (*N*=12) codes. It comprises *3×N* ONUs in system incorporating several codes. Downlink transmission in OCDMA-WDM uses 1575 nm to 1583.8 nm, generated wavelengths from continuous wave (P_{in}=10 dB) lasers by following 0.8 nm ITU-T channel spacing.

For MNZCC code, the incoming laser signals are passed through a *12×1* MUX and then forwarded to *1×4* fork. This is followed by four MNZCC encoded coded groups as *Downstream Tx_1* to *Downstream Tx_4* as depicted in Fig. 2(b). Each encoded set incorporates *1×12* DEMUX, twelve no. of sub-sections as *Subsystem 1* to *Subsystem 12* followed by an encoder. Again, each Subsystem incorporates the signal modulation of multi-wavelength coded links comprising signal format by NRZ and mach-zehnder modulator (MZM) modulator to modulate incoming signal at 10 Gbps traffic rate [34,35].

Further, the multiplexed signals by *12×1* MUX transmitted to an encoder unit for MNZCC as indicated in Fig. 2(b). A encoder unit uses a code design via utilizing distinct size *1×4* DEMUX means and similarly for another codes. Analogous to DEMUX size, MUX iscincorporated as per code design. After this, the encoded signal is modulated again using NRZ and MZM at 10Gbps. Likewise, four coded signals transferred to a *4×1* MUX then delivered to a *2×1* MUX together with three full-duplex components of ODN viz. optical circulator, fiber-VLC link and *1×2* bidirectional splitter as depicted in Fig. 2(a).

At an ONU, downlink transmission form OLT is transferred to four MNZCC decoders by incorporating a *1×12* DEMUX. Encoder and decoder follow the same code design for a specific code as exhibited in Fig. 2(c). A decoder section comprises distinct *1×4* DEMUX as well as *4×1* MUX combinations as well as succeeded by *12×1* MUX together with *1×3* Fork as realized for encoder unit to realized total 36 users (=12×3 users). In receiver section, PIN photo detector (PD), Bessel filter of low pass, 3R regenerator as well as BER analyser is used to identify the system performance.

Fo RGB based VLC in downlink, NRZ-PRBS is used to modulate each LED signal means red, green as well as blue incorporating MZM modulator followed by triple signals are multiplexed via a *3×1* MUX to forward to bidirectional components viz. optical circulator, fiber, power splitter and then VLC link. VLC performance is realized in receiver [34,35].

2.1.2. Upstream design

Uplink transmission in hybrid WDM-OCDMA PON transmission incorporates 1260-1268.8 nm wavelengths for 0.8 nm spectral width are used for distinct codes. Each ONU consists of the combination of a CW lasers (P_{in}=0 dBm), 2.5 Gbps NRZ and MZM components for modulation as depicted in Fig. 2(d). Then, generating 12 no. of uplink signals *12* multiplexed wavelengths via *12×1* MUX passed by *1×4* Fork as well as four different Upstream Txs. Each Tx incorporates a Subsystem comprising a *1×12* DEMUX along with twelve no. of Subsystems at definite time switching of received signals utilizing dual set of dynamic selects components as shown in Fig. 2(d). After passing through encoder section and 4×1 MUX, the signals are passed through bidirectional fiber-VLC link. One unit optical delay is used along the link to distinguish between upstream and downstream data transmission. These received signals are investigated at an OLT side in receiver section. Buffer secretor is utilized to select the recent iteration as depicted in Fig. 2(e). Uplink transmission in VLC comprises identical components same as downstream VLC except an opposite VLC is incorporated in ODN. Table 1 presents system parameters for single mode fiber (SMF)-VLC [34,35]. Table 2 exhibits the code design of MNZCC code.

Table 1. Integrated SMF-VLC parameters [34,35]

Parameter	**Value**
SMF range	10-70km
VLC range	0.5-10m
Temperature	300k
Attenuation	0.21dB/km
Dispersion slope	0.074ps/nm^2/k
Tx/Rx Aperture diameter	10-30cm
Dispersion	16.75ps/nm/km
Beam divergence angle	1108mrad

Table 2. MNZCC code design (weight=3, length=12, users=4) [36]

DN/UP Wavelength (nm)	**1575/ 1260**	**1575.8/ 1260.8**	**1576.6/ 1261.6**	**1577.4/ 1262.4**	**1578.2/ 1263.2**	**1579/ 1264**	**1579.8/ 1264.8**	**1580.6/ 1265.6**	**1581.4/ 1266.4**	**1582.2/ 1267.2**	**1583/ 1268**	**1583.8/ 1268.8**
User1	**1**	0	0	0	**1**	0	0	0	**1**	0	0	0
User2	0	**1**	0	0	0	**1**	0	0	0	**1**	0	0
User3	0	0	**1**	0	0	0	**1**	0	0	0	**1**	0
User4	0	0	0	**1**	0	0	0	**1**	0	0	0	**1**

3. Numerical analysis

3.1. VLC channel model

In proposed design, LOS channel is implemented in VLC system as this channel model helps in obtaining peak transmission rate with minimum fiber-VLC link interference as well as loss. Comprehensive expression of received signal (P_r) from a LOS LED is expressed as [35]:

$$b(t) = a(t) * g(t) + n(t) \tag{1}$$

where $b(t)$, $a(t)$, $g(t)$ and $n(t)$ signify received signal, transmitted signal, VLC channel impulse response as well as noise in VLC system respectively. '*' symbol depicts convolution operation. *n(t)* a VLC Gaussian noise independent signal depicts background noise as shot, ambient light and thermal noise. P_r is defined as [35]:

$$P_r = g(0)P_i \tag{2}$$

where, $g(0)$ as well as P_i mean current gain of VLC as well as Tx source power. Thence, detector current, $I(t)$, along with shot as well as thermal is expressed as [10]:

$$I(t) = \eta P_i(t) * g(t) + n(t) \tag{3}$$

where η presents detector responsivity. Further, noise can be written w.r.t. σ_t as well as σ_s thermal as well as noise (shot) variance considerably as [35]:

$$n = \sigma_t^2 + \sigma_s^2 \tag{4}$$

where

$$\sigma_s^2 = 2eR_r(P_r + P_n)B \tag{5}$$

and

$$\sigma_t^2 = \frac{4KT}{BR} \tag{6}$$

where e, R_r and P_n indicate electron change, resistance and noise power considerably. B, R, K and T indicate bandwidth at receiver, resistance, Boltzmann's constant as well as temperature respectively.

3.2. Impact of chromatic dispersion

In the proposed system, CD, D_{Fiber} at 1550 nm ref. wavelength, L for wavelengths in downlink and uplink is indicated as [34]:

$$D_{Fiber} = L[D + S(\lambda - 1550)] \tag{7}$$

where D and S mean dispersion as well as slope coefficient distinct wavelengths of λ.

Table 3 shows the measured CD for different link ranges of downlink and uplink wavelengths of considered hybrid VLC-OCDMA-WDM PON system over 60 km fiber length.

Table 3. Measured CD for the proposed system

Wavelength (nm)		CD(ps/nm)
Downlink	1575	1200
	625	170
	525	384
	455	156
Uplink	1260	-250
	625	-320
	525	-240
	455	-220

In Table 3, CD's positive and negative values present short wavelengths progress earlier comparative to long wavelengths & vice-versa. Thence, the highest achieved downstream (≤1176 ps/nm) and upstream (≤18817 ps/nm tolerance) fibre length is ≤60 km and >60 km considerably. The simulation proof in Optisystem v.17 software is presented in Section 4.

3.3. Impact of inter-symbol interference

Due to presence of dispersion, overlapping of adjacent bit intervals produces optical pulse broadening ($\triangle b$) which is known as ISI and given as follows for the proposed system as [34]:

$$\triangle b = DL\triangle\lambda \tag{8}$$

where $\triangle\lambda$ is the pulse spectral linewidth having value 0.4 nm integrated WDM-OCDMA-PON whereas for VLC system this is quite high and can be ignored ISI in VLC system. Thus, Table 4 illustrates the evaluated pulse spread over 10-60 km fiber distance analogous to the downlink and uplink transmission. Here, $\triangle\lambda$ value enhances with the increment in fiber; thence performance of design diminishes.

Table 4. Evaluated pulse spreading for the proposed system

Length (km)	Pulse spread (ps)
10	19
15	37
35	57
45	71
55	89
65	93

3.4. Impact of four wave mixing

The effect of four wave mixing (FWM) with no. of FWM signals, M for N links in designed is reported as [34]:

$$M = \frac{N^2}{2(N-1)} \tag{9}$$

Hybrid VLC-OCDMA-WDM PON utilizing distinct OCDMA codes comprises 4 for MNZCC, 3 for hadamard, 4 for ZCC, 4 for SZCC, 6 for FCC and 7 for MQC codes correspondingly. However, as the no. of channels upgrades the no. of FWM signals also rises. Also, with increase in throughput, FWM produces side lobes results in degrade in designed performance.

4. Results and discussion

Hybrid VLC-OCDMA-WDM PON performance employing three LEDs for per channel 10 Gbps downstream and 2.5 Gbps upstream transmission is analysed under influence of fiber disturbances. The simulated performance investigation of system is designed in OptiSystem v.17. The designed system performance is evaluated at 1575 nm as well as 1260 nm wavelengths for OCDMA-WDM PON downlink and uplink transmission considerably. While RGB LED-based VLC performance is analysed for three wavelength viz. red, green and blue in downlink and uplink directions. The performance of design is analysed w.r.t. quality factor (Q-factor), BER, eye patterns, received power (P_r) and OSNR considering VLC channel's ambient, shot and thermal noise besides the fiber impairments.

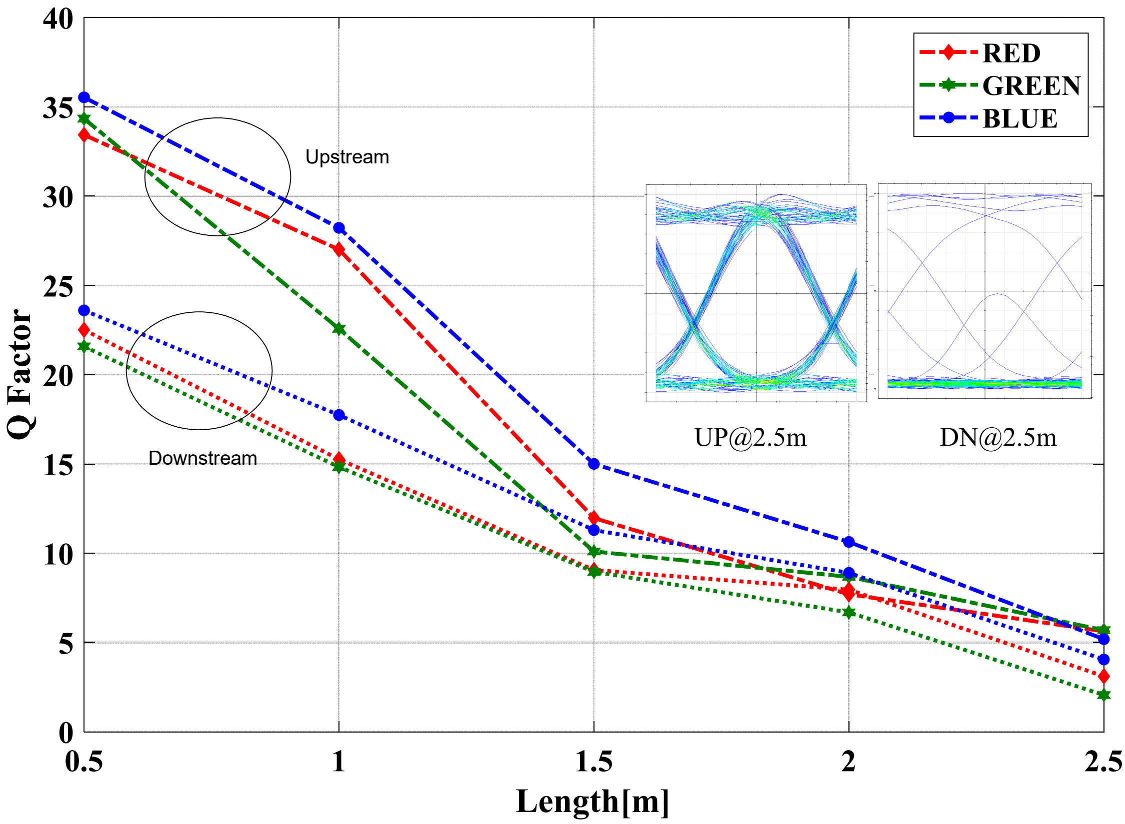


Fig. 3. Q-Factor vs. VLC length of the hybrid WDM-VLC-OCDAM PON; Insets: DN and UP eye patterns (color online)

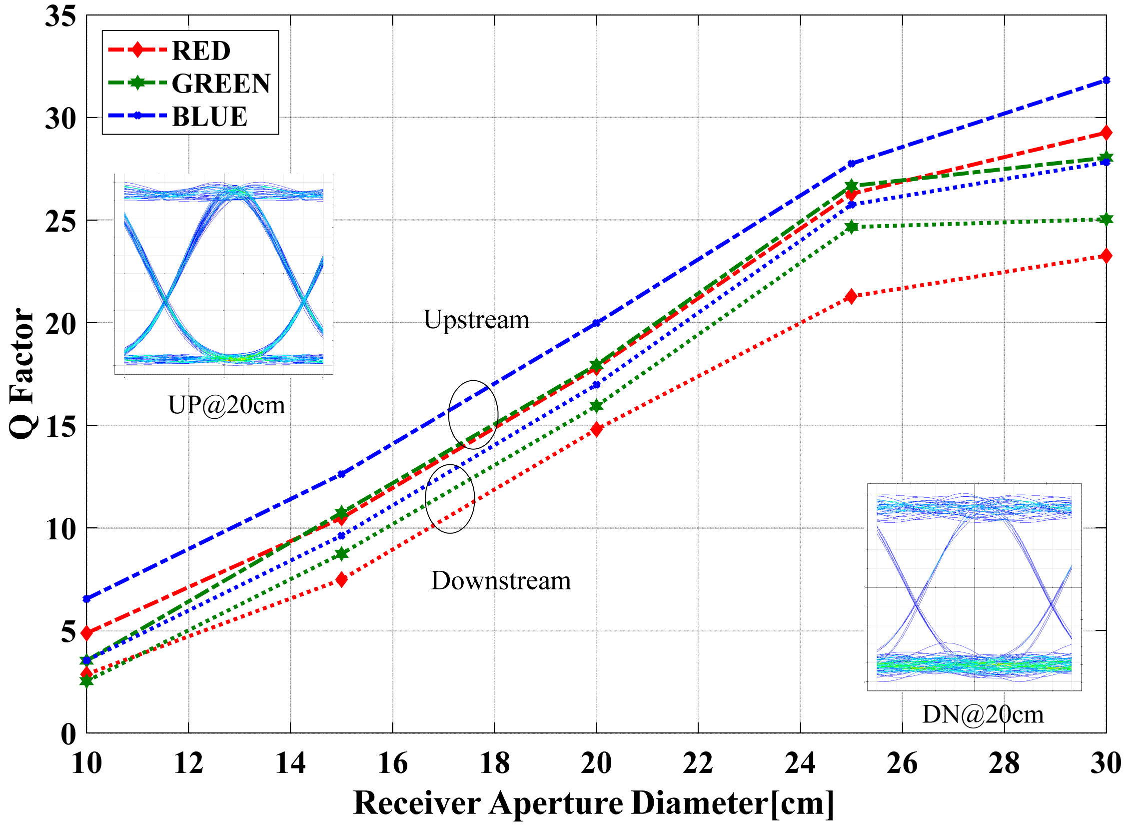


Fig. 4. Q-Factor vs. aperture diameter at receive of hybrid WDM-VLC-OCDAM PON; Insets: DN and UP eye patterns (color online)

Fig. 3 illustrates Q factor vs. VLC channel length for designed system downstream and upstream transmission employing MNZCC code at aperture diameter of 10 cm at transmitter and receiver and 10 km fiber length. It is noted that maximum supportable VLC range for designed system is 2 m for blue LED accompanied by red as well as green in downstream while it is 2.2 m for blue and 2 m for other two LEDs in upstream transmission with Q-factor limit of 6. It is noted that as the VLC range enhances, the coded input would diverge gradually. Although uplink VLC link performs superior over downstream (having data rate of 10Gbps and source power of 10 dBm) due to the influence of low source power & throughput (0 dBm & 2.5 Gbps) in uplink transmission. Therefore, it is depicted that hybrid VLC-fiber (10 km + 0.5-2.5 m) performs optimum with tolerable ≥6 Q factor using blue LED than others for uplink as well as downlink transmission. Opened %age of eye diagram at uplink 2.5 m length for blue and downstream transmission indicates system feasibility under the influence of fiber impairments as well as VLC link noise.

Fig. 4 indicates the receiver aperture diameter w.r.t. Q factor for the proposed system over 1m wireless and 10 km wired length at transmitter aperture diameter of 10 cm. The result indicate that Q value increases with an increase in receiver aperture diameter for both downstream and upstream transmission where blue LED presents best performance than others two. In upstream data transmission, red, green and blue maximum obtained Q factor of 29.26, 28.04 and 31.82 at respectively at 30 cm receiver aperture diameter. Also, for the same aperture diameter in downlink, the achieved Q factor is 23.26, 25.04 and 27.82 for red, green and blue LEDs respectively. The clear eye patterns at 20 cm receiver aperture diameter in downlink and uplink for blue LED in upstream transmission indicates the viability of designed system.

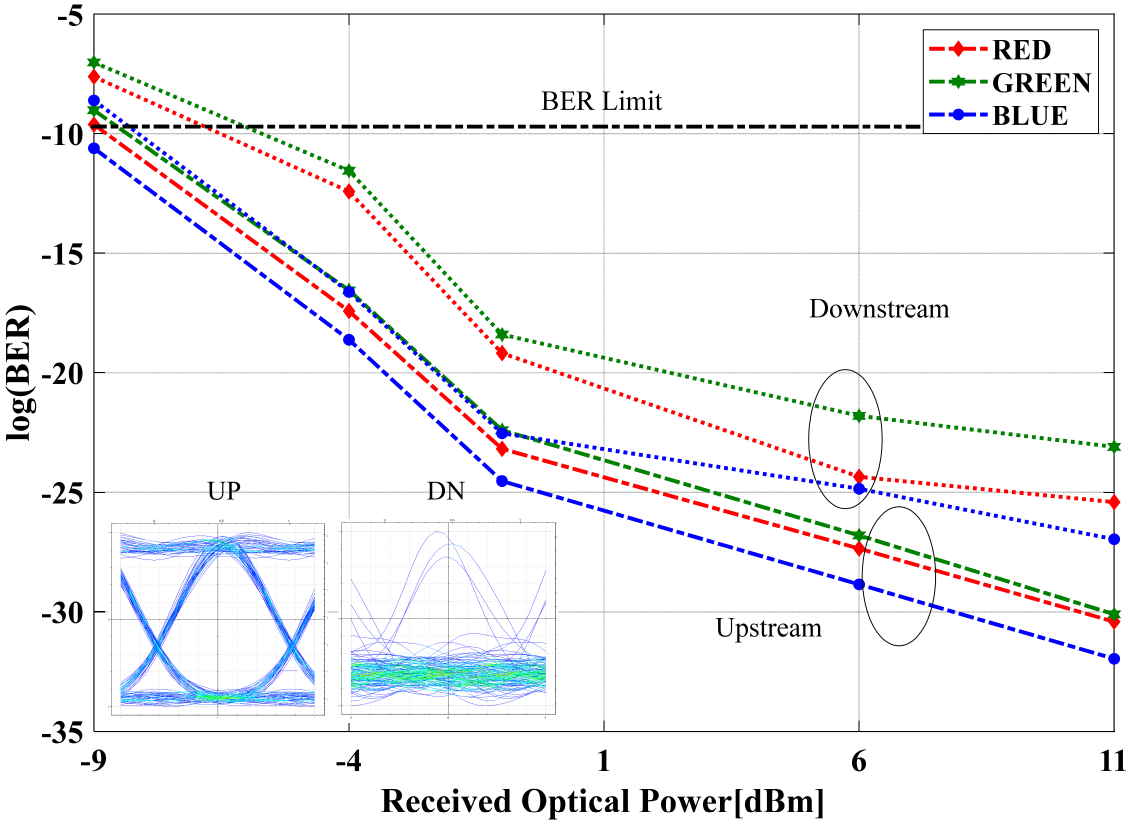


Fig. 5. log(BER) vs. received power of hybrid WDM-VLC-OCDMA PON; Insets: DN and UP eye patterns (color online)

Fig. 5 depicts the log(BER) w.r.t. received power of designed fiber-VLC link employing MNZCC code (2.5 m+10 km fiber) having both the receiver and transmitter aperture area of 10 cm. To measure BER, Gaussian approximation is regarded and measured BER in terms of signal to noise ratio (SNR) for the proposed system is given as below [34]:

$$BER = \frac{1}{2} erfc\sqrt{\frac{SNR}{8}} \tag{10}$$

where $erfc$ means error function.

From the obtained results, it can be noted that as the P_r value increases, itsperformance progress linearly in terms of decreasing BER value for two way communication.

In uplink, BER in log is -9.62 to -30.41 for red, -9.02 to -30.10 for green and -10.61 to -31.96 for blue LEDs. At acceptable $\leq 10^{-9}$ BER which depicts that blue LED indicate superior performance accompanied by red as well as green at P_r = -9 to 11 dBm. Although, in downlink transmission, blue LED having acceptable -9 log(BER) till -9 dBm, indicates finer performance irrespective of other LEDs. Upstream transmission allows better performance compared to downstream. Moreover, eye diagrams at P_r = -9 dBm for blue LED in downlink and uplink direction shows the better performance in upstream than downstream.

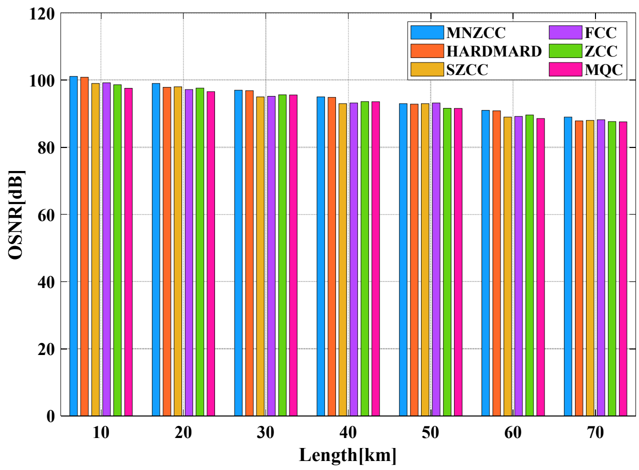


Fig. 6. OSNR(dB) Vs. fiber length of hybrid WDM-VLC-OCDAM PON (color online)

Fig. 6 illustrate the OSNR versus SMF length of PON-VLC system incorporating distinct codes over 10 m VLC range, 10 cm of transmitter aperture diameter and 30 cm aperture diameter at receiver for downstream transmission. The OSNR value with reference noise power of 100 dB, can be measured by as follows [34]:

$$OSNR = 10log_{10}\left(\frac{Signal\ Power}{Noise\ Power}\right)\ dB = Signal\ Power(dB) - Noise\ Power(dB) \quad (11)$$

where 100 dB is the reference value of noise power.

It is revealed that OSNR diminishes linearly with rise in fiber length for distinct respective codes. Out of all codes, MNZCC (OSNR= 101.11 dB) indicates optimum performance accompanied by hadamard (OSNR= 100.85 dB), SZCC (OSNR= 99.02 dB), FCC (OSNR= 99.18 dB), ZCC (OSNR= 98.62 dB) and MQC (OSNR= 97.55 dB) over 70 km fiber length. It is because of less ISI, noise and code's unique properties like zero-cross correlation, highest auto correlation and capability to handle large no. of users. Table 5 shows the comparative performance of designed system with existing recent models. It indicates that designed model provides a maximum data rate, wired and wireless link range as compared to other existing work.

Table 5. Comparison of proposed system employing RGB-LED based VLC system with existing models

Reference	Optimum wireless range (m)	Optimum fiber length (km)	Optimum datarate per channel (Gbps)
[10]	20	not defined	2×10^{-5}
[18]	1.1	not defined	1.6
[21]	2	not defined	1.57
[23]	10	50	10
[30]	4.5	20	10
Proposed work	10	70	10/2.5

5. Conclusion

Full-duplex hybrid OCDMA-WDM PON incorporating several OCDMA codes like MNZCC, MQC, ZCC, hadamard, FCC and shift ZCC with RGB-LED based VLC system under VLC link noise as well as fiber impairments over long reach at transmission rate of 10/2.5 Gbps per channel for 39 subscribers is demonstrated. It is deduced that to enhance the realization of system bi-directionally as to wireless transmission distance as well as received optical power, blue LED in the bidirectional proposed system shows best performance than red and green LEDs. It is analysed that in the proposed system with fiber length of 10 km, blue LED shows optimum maximum VLC channel range of 2.2 m at 10 cm aperture diameters at transmitter as well as receiver. Also, the received optical power of -9 dBm is received for the same system using blue LED. To further boost the system performance, VLC link receiver aperture diameter can be increased. Moreover, for 10 m of VLC range with aperture diameter at transmitter as well as receiver of 10 cm and 30 cm considerably, 70 km faithful fiber length with OSNR of 101.11 dB can be attained in system using MNZCC code. Further, the mathematical analysis shows that uplink signals perform superior over downlink under fiber non-linearities, dispersion, interference, FWM and VLC link noise. Furthermore, on comparison with previous exiting previous work, a high-speed hybrid OCDMA-WDM PON employing MNZCC code expresses ability to handle several users, long-reach, data rate as well as security.

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