



Development and investigation of 5G fiber-wireless access network based hybrid 16×10 Gbps 2048 split TWDM/DWDM super PON for IoT applications

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Abstract

Super-passive optical network (Super-PON) is considered as choice for the operators to scale the transmission speed, reach, to build new infrastructure and customer aggregation of optical access networks. To extend the reach, transmission rate and number of subscribers passively, the fifth generation fiber-wireless (5G FiWi) access network based bidirectional hybrid 16×10 Gbps time and wavelength division multiplexing/ dense wavelength division multiplexing (TWDM/DWDM) Super PON with 2048 split ratio is designed and investigated. Enhanced performances of quality factor, bit error rate (BER) and received power are observed for varying wireless range, data rate, additional losses, transmitter/receiver pointing errors and different weather conditions in the FiWi based hybrid TWDM/DWDM Super PON system. The results show that the system can offer faithful -22 dBm received power and aggregate symmetric transmission rate of 16×25 Gbps over 50 km fiber reach with 10 km wireless range in the presence of losses and pointing errors of wired/wireless channel. With tolerable $6 \mu\text{rad}$ transmitter and $3 \mu\text{rad}$ receiver pointing error for both downstream and upstream direction, the designed FiWi link transmit the information successfully. In addition, the maximum acceptable wireless reach for the proposed system is 110 and 120 km for downstream and upstream transmission respectively along with 50 km fiber range serving 2048 users for future based internet of things (IoT) applications. Additionally, the comparative performance of the proposed bidirectional 5G FiWi access network based hybrid TWDM/DWDM Super PON with 2048 split shows its superiority relative to existing models.

Keywords 5G · IoT · FiWi · Super-PON · TWDM · DWDM

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1 Introduction

In the last few years, the telecommunication network has been changing dramatically and rapidly. The emergence of novel multimedia streaming and cloud services like online gaming, online video on computers and smartphones, high-definition television (HDTV) over Internet, internet of things (IoT) deployment and optical fiber and wireless communications at the new paradigm of fifth generation (5G) technology are demanding changes to the existing networks to enable extensible growth in high bandwidth, while sustaining a top-level of dynamic connectivity, high energy efficiency and full flexibility (Sarmiento et al. 2018). Consequently the current broadband access networks are evolving towards acceptance of all-optical solutions and are influencing both optical and optical wireless channel (OWC) technologies with consistent convergence, resulting in fiber wireless (FiWi) access networks. FiWi networks combine robustness, reliability, flexibility and capacity of optical networks and the ubiquity and cost effectiveness of wireless network (Murugan 2019). In this scenario, the exploding mobile data traffic has directed the requirement for an advance optical access network for long-reach, high transmission rate and high capacity hybrid wired/wireless access network (Ebrahimzadeh and Maier 2019). In this context, hybrid passive optical network (PON) and OWC have been emerged as the promising solution in terms of distortion-free transmission of triple-play data, voice and video services. By using fiber cable as a feeder throughput and OWC as a secure, unlicensed and wireless access for foreign space communication and terrestrial applications, the hybrid PON/OWC is most suitable for future communications (Mallick et al. 2018a; Mandal et al. 2018; Mukherjee et al. 2020). Today, PONs are widely used access networks because of simple architecture building and operation in cost effective way to serve various users with a single optical fiber from the central office (CO) to optical network units (ONUs) passing through passive optical distribution network (ODN) and offering high bandwidth to end users by enabling high speed transmission (Nguyen et al. 2020; Shaddad et al. 2012).

Figure 1 presents the architecture of a conventional PON deployment with a fiber from CO serving 64 subscribers over maximum 20 km transmission distance. A downstream 1.25 Gbps wavelength division multiplexing/optical code division multiplexing (WDM/OCDMA) using reflective semiconductor optical amplifier (RSOA) over 20 km wired and 2 m wireless distance to server 16 users is successfully proposed (Cao and Gan 2012). The limited transmission distance of 20 km is because of optical power budget constraints and hence it is associated to the split ratio of the ODN. Extension of reach for different multiplexing PONs by utilizing amplifier has been reported in (Iannone et al. 2017; Kachhatiya and Prince 2016; Li et al. 2014; Luo et al. 2013; Shaddad et al. 2014). Further, a 2.5 Gbps PON with 64 split ratio over 75 km is demonstrated (Wang et al. 2010). A 20 Gbps gigabit PON (GPON) with 32 split ratio over 1000 km distance is demonstrated successfully (Aneesh et al. 2016). In addition, a hybrid fiber-to-the-x (FTTx) and free space optics (FSO) system over 20 km wired and 4.8 km FSO range at 1 Gbps supporting 32 users is proposed (Ahmad Anas et al. 2012). Also, a full-duplex hybrid WDM/time division multiplexing PON (WDM/TDM PON) employing 32 split ratio is realized in (Huang et al. 2013). A downstream optically-amplified 2.5 Gbps PON with 64 split over 60 km is successfully demonstrated (Suzuki et al. 2006). A GPON based hybrid 2.5 Gbps WDM/TDM-PON over 25 km transmission distance to serve 64 users is reported (Aldhaibani et al. 2013). A gigabit Ethernet PON (GE-PON) with 8 split ratio at 10 Gbps transmission rate over 15 km is investigated (Kaler and Kaler 2011). A 2 Gbps GE-PON architecture with 56 split ratio over 20 km transmission distance is evaluated (Kocher et al. 2013). However,

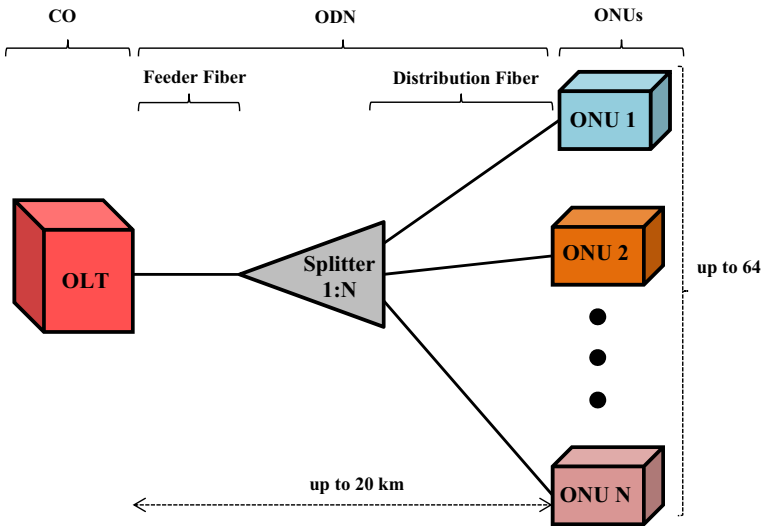


Fig. 1 Basic PON deployment

these multiplexing techniques have limited commercial applications (Kocher et al. 2013), (Huang et al. 2013), (Kaler and Kaler 2011). Moreover, the transmission speed of PONs has improved significantly during the past years. The primary gigabit speeds of EPON (1/1 Gbps) and GPON (2.5/1.25 Gbps) describe the PONs' majority installed to date. Although, in today's access technology, PON's speed of choice is 10 Gbps for new deployments. The 10G-PON's variant i.e. both 10G-EPON and next generation GPON (XG-PON) specifications are effective in providing a 10/10 Gbps service. Looking into future high transmission speed (> 10 Gbps), transmission distance (> 20 km) and to serve large number of subscribers, the modern PON technologies need to build infrastructure which is most costly component of an access network. A significant spatially scalable optical solution means Super-PON, offering improved reach and more subscriber per feeder optical fiber, would be useful for this case. Super PON is capable to support an improved reach till 50 km serving 1024 subscribers per fiber over an ODN as illustrated in Fig. 2 (DeSanti et al. 2020).

The advantages of Super-PON are most effective in various countries such as India, Indonesia, Brazil, Thailand, Vietnam, South Africa, Philippines, Kenya and many more. With its maximum reach and greater customer handling capability, Super-PON is especially desirable as an attractive solution to offer service to more infrequently populated areas. The superiority of Super-PON over conventional PON along with advantages is as follows:

- a. As compared to widely deployed the conventional PON networks and their successors such as EPON, GPON etc., super-PON has been preferred by Google Fiber to enhance fiber efficiency and minimise the number of OLTs required for network support for new internet service providers (ISPs) (Willner 2019).
- b. A Super-PON technology can support more subscribers (~ 1000) and longer transmission distance (~ 100 km) as compared to existing PONs (Willner 2019).
- c. Super-PON helps in minimising the throughout total cost for access network with simpler network maintenance and operation (Willner 2019)

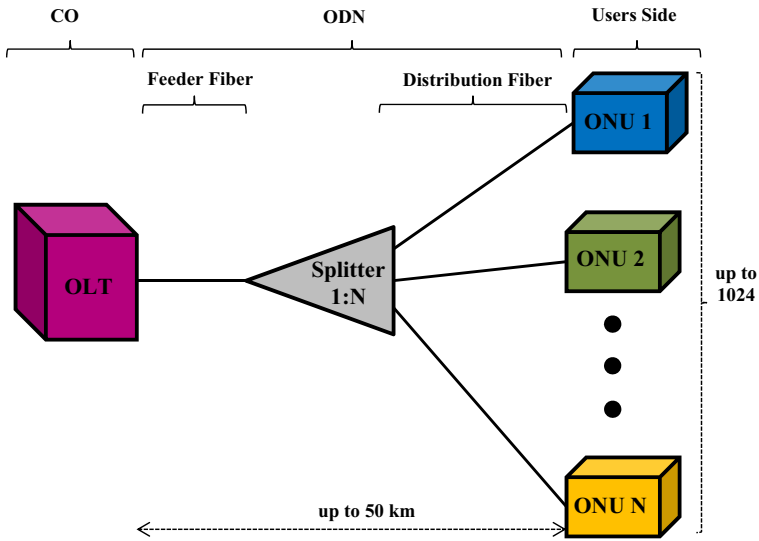


Fig. 2 Typical Super-PON deployment

Besides these advantages, Super-PON has an issue regarding high cost of ONU (user equipment) as compared to next-generation PON (NG-PON) based conventional GE-PON or XG-PON ONU as its laser transmitter requires the capability to operate on a limited wavelength-stabilized WDM channel and may require to support multiple wavelength channels if the operate desire to minimise the quantity of inventory part numbers. Thus, it has been observed that an advanced fiber access network technology is required for future applications. In this response, NG-PON stage 2 (NG-PON2) based time and wavelength division multiplexing PON (TWDM-PON) is considered as the best technology for future generation PON systems by full service access network (FSAN) because it has various attractive advantages such as management, flexibility, bandwidth upgradability, reuse of existing ODN, high split ratio, high capacity and less cost at high system performance as compared to past deployed standards. Therefore, this technology is supreme player for various network operators needs to design the Super-PON (Bindhaiq et al. 2017). Again, combining TWDM-PON architecture with OWC technology at user end is the major focus and ideal choice for recent and future research as OWC technology is viewed as an alternative to fiber cables when the physical links are impractical (Memon et al. 2019). In (Shaddad et al. 2014), FiWi access network based hybrid WDM/TDM-PON at 2.5 Gbps wired over 50 km and 54–30 Mbps wireless transmission rate over 5 m distances with 32 split ratio is designed successfully. A bidirectional 40/10 Gbps TWDM-PON with 512 split ratio over 20 km transmission distance is presented successfully in (Luo et al. 2013). In (Kachhatiya and Prince 2016) a bidirectional 10/2.5 Gbps per wavelength TWDM-PON with 1024 split ratio over 40 km is proposed and simulated. Also, in (Li et al. 2014), a symmetrical 40 Gbps TWDM-PON with amplifier over 100 km transmission distance to support 1024 subscribers is reported. In (Iannone et al. 2017), 80 Gbps full-duplex TWDM-PON with 256 split ratio over 42 km is demonstrated.

Further, to achieve the high data rate with high capacity and cost effective architecture, dense wavelength division multiplexing (DWDM) technique is most preferably used with PONs for 5G FiWi access network. A symmetrical bidirectional 10 Gbps DWDM-PON

over 42 km reach to serve 80 subscribers is demonstrated (Zhang et al. 2015). A 1.25 Gbps orthogonal frequency division multiplexing (OFDM) DWDM-EPON network with 32 split ratio over 20 km is successfully demonstrated (Sharma and Sharma 2014). A hybrid 25 Gbps mode division multiplexing (MDM) and DWDM-PON with 15 split ratio over 1 km reach is reported (Fazea 2019). A 15 Gbps DWDM ring topology network with 13 channels over 70 km is investigated (Singh 2014). In addition, a downstream 2.5 Gbps WDM-PON system over 80 km reach to support 32 subscribers is reported (Singh et al. 2013).

On the basics of various published papers presented in this paper, the objectives are given as follows:

- a. However FiWi systems can be a worthy solution for various broadband access networking requirements, there are some significant limitations such as fog, rain, snow, dust or smog atmospheric conditions along with channel additional loss which can restrict the transmission path, transmission rate and capacity of the system.
- b. As till now most of research is done on WDM, TDM, OCDMA and OFDM PON but not on FiWi based hybrid TWDM/DWDM Super PON system.
- c. The proposed system can help to reduce the access infrastructure building as well as operating cost.
- d. The motivation of the proposed future-proof 5G FiWi based hybrid TWDM/DWDM Super PON is to scale the PON spatial characteristics along with scaling high transmission speed for 5G and IoT applications.

The real-life usefulness and evidence of the viability of Super-PON is Google Fiber. Google Fiber is an exploratory version of Super-PON in San Antonio, USA. Super-PON (with 2048 split ratio and more) has been preferred by Google Fiber to enhance fiber efficiency and minimise the number of OLTs required for network support for new internet service providers (ISPs). Also, Super-PONs are most effective in various countries such as India, Indonesia, Brazil, Thailand, Vietnam, South Africa, Philippines, Kenya and many more (Desanti et al. 2020; Lam 2007; Willner 2019).

The paper is organized as Sect. 2 presents the designed FiWi based hybrid TWDM/DWDM Super PON system, Sect. 3 and 4 present the results and discussions followed by conclusion respectively.

2 Proposed bidirectional 5G FiWi based TWDM/DWDM super PON system with 2048 split ratio

The FiWi based TWDM/DWDM Super PON system serving 2048 users for 5G and IoT applications system can be used for different applications such as a high-speed full-duplex fully connected OWC system and it is comparable to wireless-fidelity (Wi-Fi), which utilizes radio waves for wireless communication. As compared to Wi-Fi, FiWi is a more effective solution that can be used in electromagnetic radiation-sensitive areas (e.g. aircraft, hospitals, chemical plants) and supports IoT applications at a high data rate of 10 Gbps. Also, FiWi system can be utilized for vehicular communication because of the presence of the existing traffic light as well as vehicle lights infrastructure. This system offers pre-crash sensing along with lane change warning, left turn assistant, speed warning, stop sign movement etc. Radio waves do not proceed in seawater due to their absence of good conductivity in water. Thus, the FiWi communication system should be utilized in underwater

connecting networks. Besides this, in the hospital, sensitive areas of electromagnetic wave-like magnetic resonance imaging (MRI) scanners are probably switched to the FiWi system as OWC signals will not interfere with the RF waves of the other machines. FiWi system can be utilized as a PON-OWC based identification (ID) system in several places like subways and buildings. It can be used for recognizing the buildings' room numbers. Also, the ID system can be utilized in hospitals, airports and subways. FiWi based TWDM/DWDM Super PON system can be utilized in setting up wireless local area networks (WLANs). For high-speed WLANs, star topology architecture using fiber/wireless link along with TDM or frequency division multiplexing (FDM) for downlink and uplink transmission is used. Thus, WLANs can be utilized in hospitals and buildings that require high security (Khan 2017).

Figure 3 presents the schematic of the proposed FiWi based bidirectional 16×10/10 Gbps based hybrid TWDM/DWDM Super PON system supporting 2048 subscribers using OptiSystem v.16 software.

In the proposed bidirectional FiWi based TWDM/DWDM Super PON system, eight downstream and eight upstream wavelengths are utilized for downstream and upstream TWDM/DWDM communication links. In OLT section, a downstream transmitter section, the pseudo random bit sequence (PRBS) generator generates bit pattern at data rate of 2.5–30 Gbps together with non-return to zero (NRZ) pulse generator followed

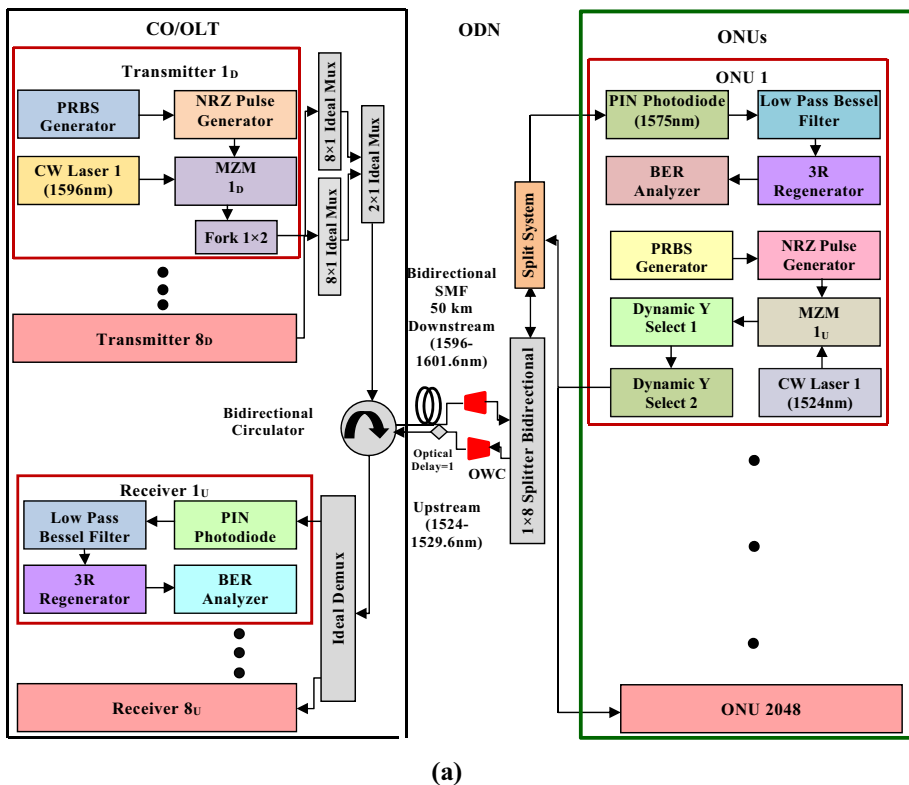


Fig. 3 (a) Schematic diagram of proposed bidirectional 5G FiWi based TWDM/DWDM Super PON system, split system for (b) downstream and (c) upstream

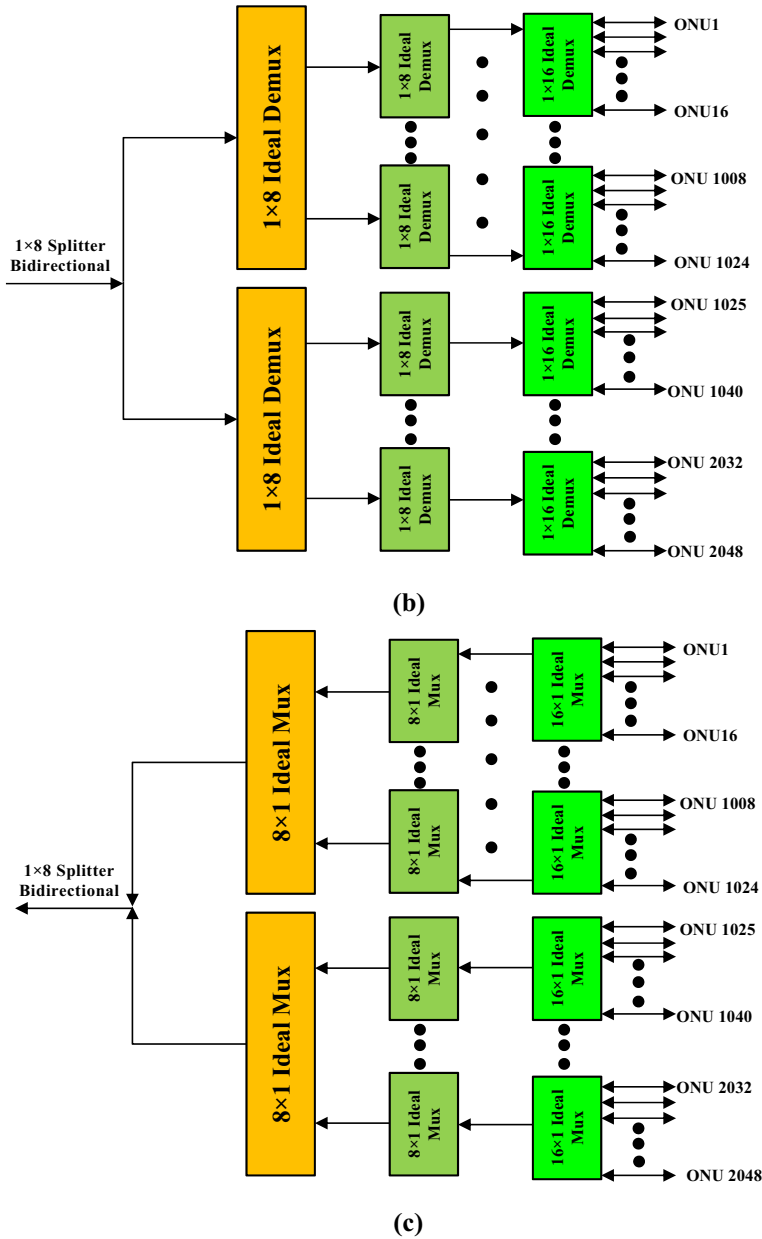


Fig. 3 (continued)

by a Mach–Zehnder modulator (MZM). Then each incoming signal is forked by a 1×2 fork component to generate the hybrid TWDM/DWDM links and passed into two 8×1 ideal multiplexers, one for TWDM and another for DWDM links followed by a 2×1 ideal multiplexer to multiplexed the transmitted signals. Again these combined signals

forwarded to a bidirectional circulator to direct the transmitting signals in a related optical band and over a bidirectional fiber (Singh and Singh 2017).

In ODN section, a full duplex single mode fiber (SMF) of 50 km transmission length is utilized by considering attenuation, dispersion, fiber non-linearity effects and noise. In fiber, an optical delay having value equal to 1 is applied in upstream direction to differentiate the downlink and uplink communication. Also, two OWC channels are used for downstream and upstream transmission. Further, a 1 × 8 bidirectional splitter is utilized along with a split system to splits the input signal power to support 2048 ONUs. The proposed split system serving 2048 ONUs is shown in Fig. 3(b) which consists of two 1 × 8 ideal demultiplexers, one for TWDM and another for DWDM signals. Each 1 × 8 ideal demultiplexers further demultiplexed into eight 1 × 8 ideal demultiplexers followed by eight 1 × 16 ideal demultiplexers to offer services to total 2048 ONUs. Likewise for upstream transmission, multiplexers are used instead of demultiplexers to transfer the data from ONU to OLT section as shown in Fig. 3(c) (Singh and Singh 2017). In ONU section, for each downstream signal reception, a PIN photodiode is used to convert the incoming optical signal into electrical signals, a low pass Bessel filter that filters the desired signal with noise immunity and 3R regenerator to regenerates the electrical signal are used. Bit error arte (BER) analyzer is utilized to monitor FiWi based hybrid TWDM/DWDM Super PON performance in terms of BER, Q-Factor, eye-height and eye diagrams real practical conditions (Soni 2017).

Again, PIN-photodiodes in Super-PON provide high-reliability, high-sensitivity, fast-response, low-noise and cost-effectiveness. Thus, PIN-photodiodes are widely used in Super-PONs at end-users side to handle packets of a wide range of optical power over long transmission distance. Because photodiodes can implemented to offer a reverse bias voltage at low voltage source (< 20 V) and provide less current noise as compared to avalanche photo-diodes (APDs). These photodiodes are more suitable for low power applications compared such as PONs with huge number of users (Lam 2007).

For the upstream transmission, eight CW lasers tuned to eight wavelengths (1524–1529.6 nm spaced by 0.8 nm) followed by 2.5–30 Gbps PRBS generator, NRZ-MZM modulation components are used generate the upstream transmission. Also, two cascaded dynamic Y selects are used to transmit the signals using TDM multiplexing. The switching time for each wavelength is given in Eqs. 1 and 2 (Shukla and Nigam 2018). For two consecutive dynamic selects Y, the switching time (T_{s1}) and (T_{s2}) expression for upstream users, N_u , is expressed as: (Alateeq et al. 2012), (Praveena et al. 2017)

$$T_{s1} = Timeslot \times \frac{1}{Bit\ rate} \times \frac{Sequence\ length}{N_u} \tag{1}$$

$$T_{s2} = Timeslot \times \frac{1}{Bit\ rate} \times \frac{Sequence\ length}{N_u} \times \frac{Time\ window}{N_u} \tag{2}$$

where *Timeslot* ranges from zero to seven, *Sequence length* equals to 128 Bits having *Time window* of 5.12×10^{-08} s.

Then, after passing through two 8 × 1 ideal multiplexer followed by a bidirectional SMF, the upstream signals are forwarded to the OLT section for upstream signals reception. For reception, again, PIN photodetector, buffer selector to select only the latest simulation iteration, low pass filter, 3R regenerator and BER analyzer are used (Praveena et al. 2017). The received signal, P_r , at the receiver is expressed as:

$$P_r = P_{tr} \eta_t G_t G_r L_t L_r \left(\frac{\lambda}{4\pi l} \right)^2 \quad (3)$$

where P_t means transmitter optical power, η_t implies transmitter optics efficiency, η_r is the optics efficiency of the receiver, λ implies wavelength, l implies range between transmitter and the receiver, G_t and G_r signify transmitter and the receiver telescope gain respectively; L_t and L_r are the pointing loss factor of transmitter and the receiver pointing loss factor respectively. The transmitter telescope gain can be given as:

$$G_t = \left(\frac{\pi D_t}{\lambda} \right)^2 \quad (4)$$

where D_t implies the diameter of transmitter telescope. Likewise, the receiver telescope gain can be given as:

$$G_r = \left(\frac{\pi D_r}{\lambda} \right)^2 \quad (5)$$

where D_r implies the diameter of receiver telescope. Also the transmitter and receiver pointing loss factor are expressed as:

$$L_t = \exp(-G_t \theta_t^2) \quad (6)$$

and

$$L_r = \exp(-G_r \theta_r^2) \quad (7)$$

where θ_t and θ_r are the transmitter and receiver azimuth pointing error angles respectively. The parameters used of various components of FiWi based hybrid TWDM/DWDM Super PON system design are given in Table 1.

3 Results and discussion

In this system, the performance of high-speed and long reach FiWi based hybrid TWDM/DWDM Super PON system with 2048 split ratio over 50 km fiber reach along with variable wireless reach under the impact of different weather conditions, additional loss, 20 cm of transmitter/receiver aperture diameter, is evaluated in terms of minimum BER of 10^{-9} , Q-factor of ≥ 6 , received optical power and eye diagrams. Here, responsivity, dark current, thermal noise and filter cut-off frequency is taken as 1 A/W, 10 nA, 1.00×10^{-22} W/Hz and 3.75×10^9 Hz respectively.

Figure 4a, b show that Q-factor versus data rate for 50 km fiber distance and 10 km OWC range under different weather conditions for downstream and upstream transmission respectively in the proposed FiWi based hybrid TWDM/DWDM Super PON system.

Figure 4a and b imply that the Q-factor decreases with increase data rates from 5 to 35 Gbps and hence performance of the system decreases for all weather conditions. Also, the highest data rate achieved for clear air, haze and rain weather conditions is 25, 22.5 and 20 Gbps respectively for downstream transmission as shown in Fig. 4a. Again Fig. 4b show that the maximum transmission rate achieved for the proposed system in uplink direction is 25 Gbps for clear air, 22.5 Gbps for haze and 20 Gbps for rain with minimum Q factor

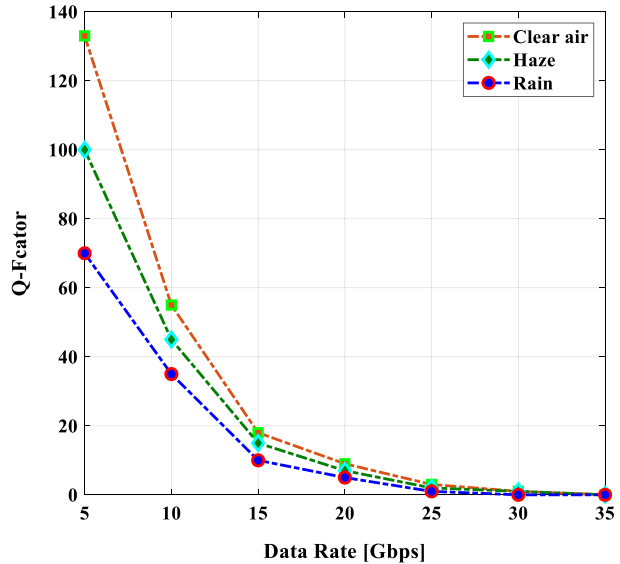
Table 1 Parameters used for proposed FiWi based hybrid 2048 split TWDM/DWDM Super PON (Alshammari et al. 2019; Dhasarathan and Singh 2020)

Parameters			Values
Bit rate (per wavelength for upstream and downstream)			2.5–30 Gbps
TWDM-PON (per wavelength)	Upstream wavelengths		1524–1529.6 nm
	Downstream wavelengths		1596–1601.6 nm
	Upstream switching time		$0-5.12 \times 10^{-8}$ s
DWDM (per wavelength)	Upstream wavelengths		1524–1529.6 nm
	Downstream wavelengths		1596–1601.6 nm
	Upstream switching time		$0-5.12 \times 10^{-8}$ s
Wavelengths spacing			0.8 nm
SMF	Attenuation		0.2 dB/km
	Dispersion		16.75 ps/nm/km
	Dispersion slope		0.075 ps/nm ² /km
	Filter cut-off frequency		3.75×10^9 Hz
	Length		50 km
OWC	Attenuation	Clear weather	0.14 dB/km
		Haze	1.53 dB/km
		Rain	6.27 dB/km
	Transmission distance	Clear weather	10–130 km
		Haze	10–130 km
		Rain	10–130 km
	Data rate	Clear weather	2.5–30 Gbps
		Haze	2.5–30 Gbps
		Rain	2.5–30 Gbps
	Transmitter aperture diameter		20 cm
	Receiver aperture diameter		20 cm
	Additional loss		1–3 dB/km
	Transmitter pointing error		1–6 μ rad
Receiver pointing error		1–3 μ rad	

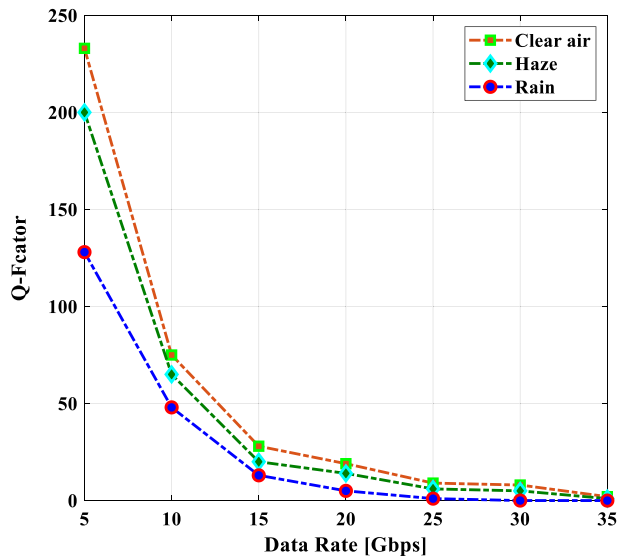
of 6. Thus, the proposed system perform better under clear air followed by haze and rain weather conditions at maximum symmetric 25 Gbps transmission rate per downstream/upstream wavelengths. Moreover, it can be estimated from Fig. 4(a) and (b) that the Q-factor of the system deteriorates with the improvement in transmission rate because of the presence of optical components i.e. laser, optical fiber, Mux/Demux, splitters etc., which cause the system degradation. Also due to the interaction of co-propagating signals, fiber nonlinearities and OWC attenuation, the performance of system decreases (Qi et al. 2011).

Figure 5a and b show that BER versus received optical power at PIN photodetector with input power (P_{in}) of 10 dBm for 50 km fiber distance and 10 km OWC range under different weather conditions for downstream and upstream transmission respectively in the proposed FiWi based hybrid TWDM/DWDM Super PON system. Figure 5a and b illustrate that as the received power increases, the BER decreases and hence system performance increases. The faithful received optical power for both downstream and upstream transmission under minimum BER of 10^{-9} is –22 dBm, –21 dBm and – 20 dBm for clear air, haze and rain weather conditions respectively as shown in Fig. 5(a) and (b) respectively. Further,

Fig. 4 Q-Factor versus data rate (Gbps) for (a) downstream and (b) upstream transmission of the proposed system for different weather conditions



(a)

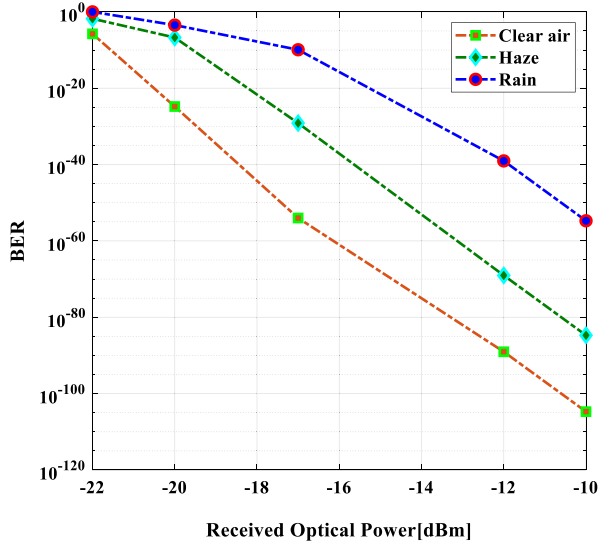


(b)

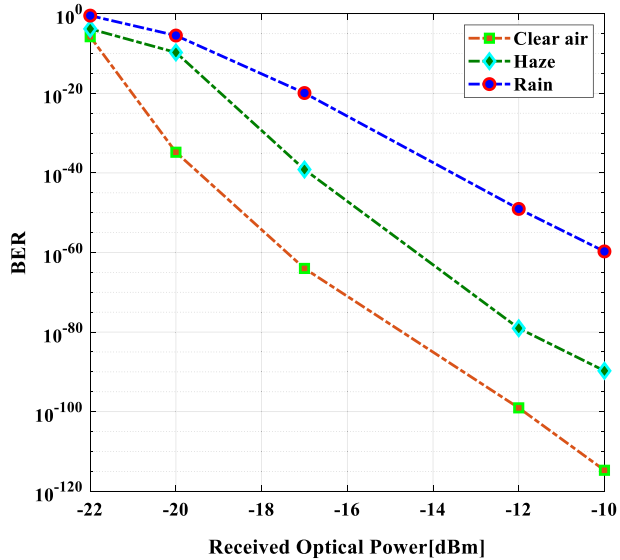
at high received power of -10 dBm, the upstream transmission shows better performance than downstream transmission in the proposed 5G FiWi based hybrid TWDM/DWDM Super PON system.

Figure 6(a) and (b) show that BER versus transmitter pointing error for 50 km fiber distance and 10 km OWC range under different weather conditions for downstream and upstream transmission respectively in the proposed Super PON system. Figure 6(a) and (b)

Fig. 5 BER versus received optical power (dBm) for (a) downstream and (b) upstream transmission of the proposed system for different under different weather conditions



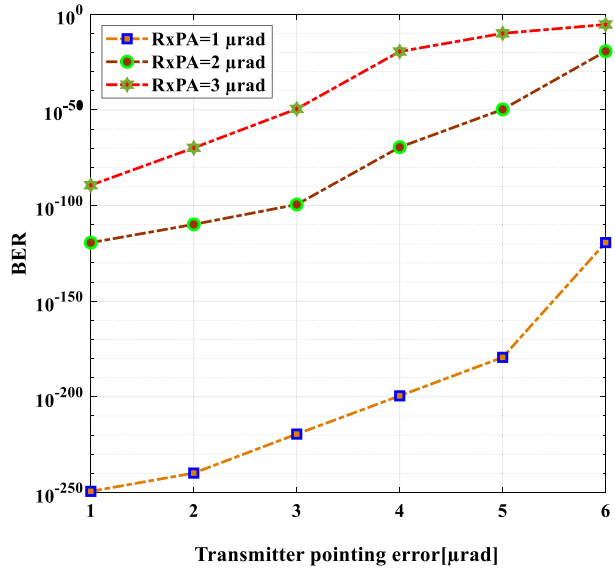
(a)



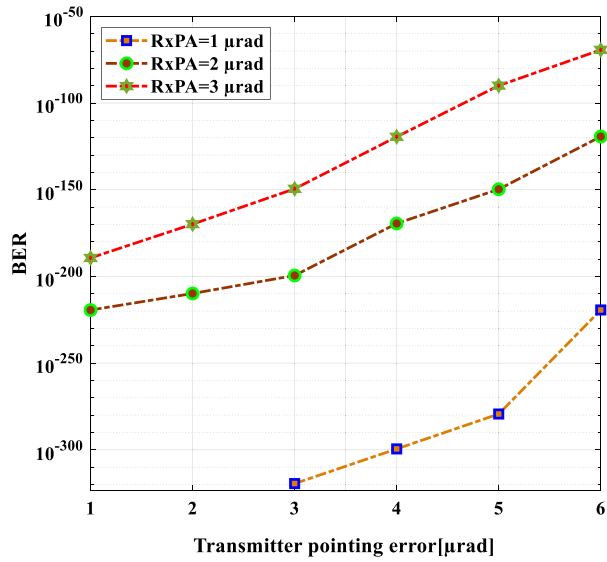
(b)

illustrate that that as the transmitter pointing error increases, the BER increases and hence system performance decreases for all variable receiver pointing error. The acceptable transmitter pointing error for downstream transmission under minimum BER of 10^{-9} is achieved for receiver pointing error of $1 \mu\text{rad}$ is more than $6 \mu\text{rad}$ while the worst for receiver pointing error of $3 \mu\text{rad}$ is $6 \mu\text{rad}$ as shown in Fig. 6(a). Again, for upstream transmission, the best performance is achieved for receiver pointing error of $1 \mu\text{rad}$ followed by $2 \mu\text{rad}$ and $3 \mu\text{rad}$ respectively, for varying transmitter pointing error of more than $6 \mu\text{rad}$.

Fig. 6 BER versus transmitter pointing error (μrad) for (a) downstream and (b) upstream transmission of the proposed FWi system for varying receiver pointing error (μrad)



(a)



(b)

Again, BER is defined as the rate at which errors generates in a communication system. It is the ratio of an average number of error bits received to the total number of bits received. It is a dimensionless quantity that estimates the probability of error (P_e) and mathematically can be described as (Kachhatiya and Prince 2016):

$$P_e = 0.5(1 - \text{erf})\sqrt{E_b/N_0} \tag{8}$$

where *erf* is error function; E_b and N_0 mean the energy in one bit and noise power spectral density (noise in 1 Hz bandwidth) respectively. Also, BER in terms of Q-factor is described as:

$$BER = \frac{1}{Q\sqrt{2\pi}} e^{-\frac{Q^2}{2}} \tag{9}$$

BER of a network can be improved by minimizing the loss in transmission media, network components and transmission medium. Table 2 shows the BER calculations for proposed work using MATLAB for receiver pointing error (μrad).

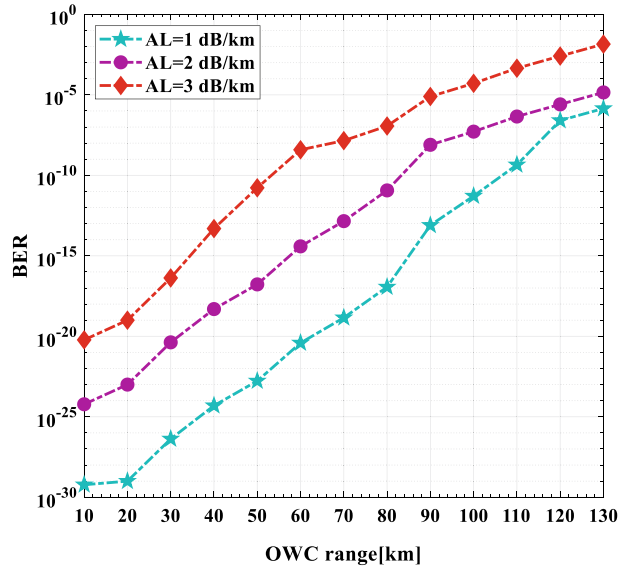
Figure 7(a) and (b) show the BER versus OWC range for downstream and upstream transmission respectively in the proposed 5G FWi based hybrid TWDM/DWDM Super PON system with 50 km fiber distance for different additional losses. It can be observed that the quality of systems deteriorates as the OWC length (10–130 km) increases because of more impactful additional losses along with pointing errors in the OWC channel in bidirectional transmission. So, the faithful downstream transmission distance corresponding to BER of 10^{-9} is 110 km, 85 km and 60 km for additional loss (AL) of 1 dB/km, 2 dB/km and 3 dB/km respectively. These results show the effect of OWC channel loss on the transmission performance of proposed system OWC reach. Also, the results from Fig. 7(b) shows that the faithful OWC range corresponding to 10^{-9} BER, for the proposed 5G FWi based hybrid TWDM/DWDM Super PON system with 50 km fiber distance in upstream direction is 120 km for additional loss of 1 dB/km, 110 km for additional loss of 2 dB/km and 100 km for additional loss of 3 dB/km. It is thus evident that the system performs better at additional loss of 1 dB/km as compared to others additional losses in upstream direction than downstream direction. Table 3 shows the BER calculations for proposed work using MATLAB for different additional losses.

Figure 8 shows that the eye diagram is widely opened for clear air weather condition as comrade to haze and rain of the proposed 5G FiWi based hybrid TWDM/DWDM Super PON system with 2048 spit ratio. Large eye opening means the signal has been faithfully received at ONU and has minimal signal distortion, noise and losses as for clear air weather condition. While for rain atmospheric condition, the eye closure is clear, which indicates the presence of fiber interference, attenuation and noise in OWC causing signal quality deterioration. Also, the deterioration in the system performance is because of presence of residual chromatic dispersion (CD) and four-wave mixing (FWM) effects in optical cable, losses and pointing error in OWC channels. Further, Table 2 shows the comparative

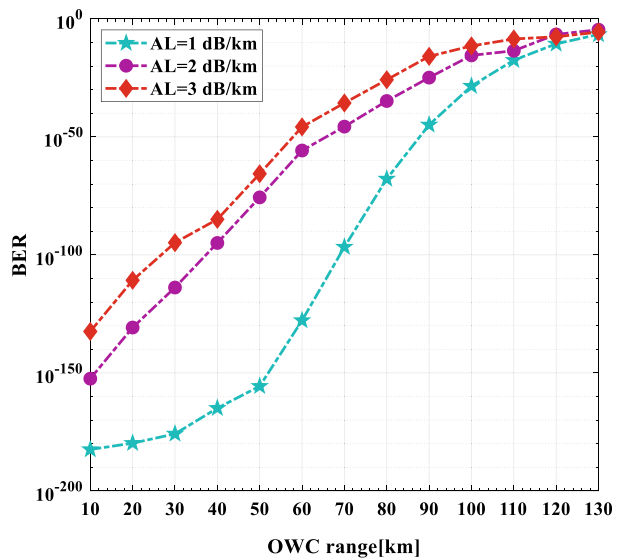
Table 2 BER calculations for proposed work using MATLAB for receiver pointing error (μrad)

Channel	Transmitter pointing error (μrad)	RxPA = 1 μrad	RxPA = 2 μrad	RxPA = 3 μrad
Downstream	1	10^{-29}	10^{-20}	10^{-18}
	3	10^{-19}	10^{-15}	10^{-13}
	6	10^{-10}	10^{-7}	10^{-5}
Upstream	1	10^{-37}	10^{-35}	10^{-31}
	3	10^{-29}	10^{-28}	10^{-23}
	6	10^{-17}	10^{-13}	10^{-10}

Fig. 7 BER versus OWC range (km) for (a) downstream and (b) upstream transmission in the proposed FiWi based Super PON system for different additional losses



(a)



(b)

performance of proposed hybrid TWDM/DWDM Super PON with 2048 split ratio, with existing systems in terms of transmission distance, data rate and number of users at a minimum acceptable 10^{-9} BER.

Tables 4 illustrates that 5G FiWi based hybrid TWDM/DWDM Super PON system with 2048 split ratio provides a maximum free space link range of 120 km, 50 km fiber

Table 3 BER calculations for proposed work using MATLAB for different additional losses

Channel	OWC distance (km)	AL = 1 dB/km	AL = 2 dB/km	AL = 3 dB/km
Downstream	10	10^{-27}	10^{-22}	10^{-17}
	50	10^{-19}	10^{-14}	10^{-9}
	100	10^{-13}	10^{-11}	10^{-3}
	130	10^{-4}	10^{-2}	1
Upstream	10	10^{-39}	10^{-36}	10^{-37}
	50	10^{-30}	10^{-29}	10^{-28}
	100	10^{-9}	10^{-8}	10^{-7}
	130	10^{-6}	10^{-5}	10^{-4}

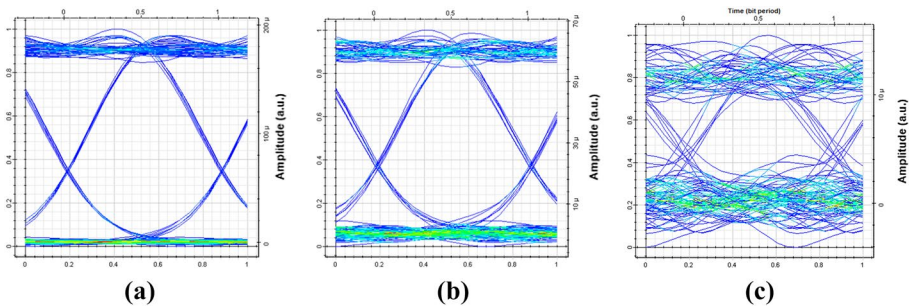


Fig. 8 Eye diagrams of received downstream signals of the proposed FiWi based Super PON system (a) clear air, (b) haze and (c) rain weather conditions

Table 4 Comparison of proposed 5G FiWi based hybrid TWDM/DWDM Super PON system with existing models under clear air weather condition @ BER of 10^{-9}

Reference	Maximum range (km)		Maximum data rate (Gbps)
	OWC	fiber	
(He et al. 2016b)	4.5	20	10
(Sheetal and Singh 2018)	10	50	2.5
(Mallick et al. 2018b)	10	50	10
(He et al. 2016b)	4.5	20	10
Proposed work	120	50	400

length and 160 Gbps data rate as compared to other models. Also, the proposed system performs better for upstream transmission as compared to downstream transmission for varying wireless range, errors and loss.

In Table 5 the proposed Super-PON network shows the better performance as compared to existing works on hybrid fiber/wireless networks in terms of high data rate, longer transmission distance and cost-effectiveness. Moreover, the power budget (PB) with receiver sensitivity (RS) at input power of 10 dBm for the proposed work over 130 km OWC link using the following Eq. (8) is determined in Table 6 (Mandal et al. 2021).

Table 5 Comparative study of cost of the proposed work

Existing networks	Maximum			Deployment cost
	Wireless range (m)	SMF length (km)	Data rate (Gbps)	
WDM fiber/VLLC (Shi et al. 2018)	5	50	3.2	Moderate
Fiber-VLLC (Wei et al. 2017)	~ 8	20.5	2.5	Moderate
Integrated PON/VLLC (He et al. 2016a)	~ 8	30.5	16	Moderate
Wireless/wired WDM PON (Shaddad et al. 2012)	~ 100	20.5	7.68	Moderate
FSO system (Mallick et al. 2019)	500	50	10	Low
Hybrid fiber/FSO system (Singh and Malhotra 2019)	3600	50	80	High
Proposed work: Hybrid wired/wireless based Super-PON under different weather conditions	130 k	50	30	Moderate

Table 6 Power Budget calculations for proposed work

Channel	PB (dB)	RS (dBm)
Downstream	30	- 20
Upstream	70	- 60

$$PB = InputPower - RS \quad (10)$$

4 Conclusion

The 5G technology provides greater quality of service, high-transmission rate and reaches ability, which necessitates the IoTs applications in the 5G framework. FiWi is considered as an optimistic and favourable choice that can fulfil potential of 5G architecture by offering more than 100 Gbps data rate transmission links. In this work, a 5G FiWi based hybrid TWDM/DWDM Super PON system with 2048 spit ratio for IoT applications is designed. The performance of the system is investigated with various impacting factor like data rate, transmitter/receiver pointing errors, additional losses, atmospheric conditions and wireless link range. Low BER of 10^{-9} and high split ratio of 2048 are observed from 25 to 20 Gbps per downstream and upstream sixteen channels over 50 km of fiber and 10 km of wireless reach under clear air to rain atmospheric conditions respectively. It is investigated that the high received optical power of -10 dBm can be achieved for symmetric 16×10 Gbps hybrid TWDM/DWDM Super PON system with 2048 spit ratio under the presence of pointing error, additional losses and clear air weather condition. With tolerable transmitter and receiver pointing error of up to 6 μ rad and 3 μ rad respectively for downstream and upstream transmission, the bidirectional signals can transmit effectively over FiWi channel with 50 km fiber and 10 km wireless range. Also, the improved wireless span of 110 km for downstream and 120 km for upstream is achieved faithfully in the presence of 1 dB/km additional losses. Accordingly,

the designed 5G FiWi based hybrid TWDM/DWDM Super PON system with 2048 split ratio offers better performance than existing wired/wireless systems in terms of wireless range, wired distance and transmission distance.

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Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declaration

Conflict of interest The authors declare that they have no conflict of interest.

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