Optical Fiber Technology 61 (2021) 102422

Contents lists available at ScienceDirect

Optical Fiber Technology

journal homepage: www.elsevier.com/locate/yofte

Hybrid FSO/fiber optic link based reliable & energy efficient WDM optical network architecture

Amit Kumar Garg [a,*], Vijay Janyani [b], Bostjan Batagelj [c], N.H. Zainol Abidin [d,e], M.H. Abu Bakar [d]

[a] Department of Electronics and Communication Engineering, Indian Institute of Information Technology, Kota (MNIT Campus), Jaipur, India
[b] Department of Electronics and Communication Engineering, Malaviya National Institute of Technology, Jaipur, India
[c] Faculty of Electrical Engineering, University of Ljubljana, Slovenia
[d] Wireless and Photonics Networks Research Centre, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia
[e] Physics Unit, Centre of Foundation Studies for Agricultural Science, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia

A R T I C L E I N F O

Keywords:
Free space optics
Optical access network
Hybrid SMF/FSO
Energy efficient optical network

A B S T R A C T

Nowadays, free space optics (FSO) is becoming popular and is very competitive to the fiber optic technology for providing broadband services at very high data rates without the requirement of any spectrum licensing. FSO links can be installed within a few hours and at a very low cost. As compared to the optical fiber, FSO links do not have any problem of faults during digging and maintenance of roads. However, during obstructive climatic conditions such rain, the FSO link losses become high and are not suitable for long-distance transmission. While the single-mode fiber (SMF) link is suitable for such conditions as the link losses are almost independent on the climatic conditions. To leverage the benefits of both FSO and SMF, this paper proposes a Hybrid FSO/Fiber Optic based dual-link architecture that is capable of transmitting data at 20GBPS for a distance up to 5 km. The FSO link is useful for clear weather conditions and fiber optic link is useful for adverse environmental conditions especially for rainy days where link losses are high and require high transmitter powers. By imposing the fiber optic link for rainy days, a significant amount of energy consumption is reduced since losses inside the optical fiber are very low. The architecture provides the reliability against the failure of any one of the links by switching the operational link to the ideal link and vice versa. The architecture supports the dedicated point to point, overlay broadcasting to transmit dedicated and common data respectively. The architecture further adds the reliability against the failure of any link between a remote node (RN) arrayed waveguide grating (AWG) to the optical networking unit (ONU), as the services may be continued on the broadcasted wavelength until the recovery of the original link.

1. Introduction

Nowadays, free-space optics (FSO) is becoming a popular solution for providing high-speed, secured, and comparatively low-cost internet services as compared to conventional radio frequency (RF) as well as fiber optic communication. FSO has become more attractive since it does not require any spectrum licensing, has no interference with the radio frequency bands and provides gigabit free space transmission [1]. FSO links are very easy to install and require very little time and cost as compared to optical fiber link. FSO links do not have the problem of link failure due to the maintenance and digging of roads. However, the performance of FSO is very sensitive to environmental conditions such as rain, fog, snow, smoke, haze, scintillation, etc [2]. The impact of fog, smoke on FSO attenuation is modeled in [3] and variation in attenuation due to rain is given in [4,5]. In presence of these environmental conditions, the losses of the FSO link may become very high as few hundreds of dB/km [6] and not able to transmit data without very high transmitted powers. Also, there may be some service interruptions in the presence of any line of sight (LOS) obstacles such as birds, moving objects or butterflies, etc. At the same time, through the optical fiber, one can transmit the signals at the very high data rate (few 100GBPS) with very low transmission losses i.e. 0.2 dB/km for SMF and approximately 2 dB/km for multi-mode fiber (MMF). However, fiber optic transmission has higher nonlinear effects and reliability problems due to fiber faults during digging or laying of new network infrastructure. The fiber optic communication requires high maintenance and implementation time as

* Corresponding author.
E-mail address: amitgroup1988@gmail.com (A.K. Garg).

https://doi.org/10.1016/j.yofte.2020.102422
Received 30 July 2020; Received in revised form 8 November 2020; Accepted 24 November 2020
Available online 21 December 2020
1068-5200/

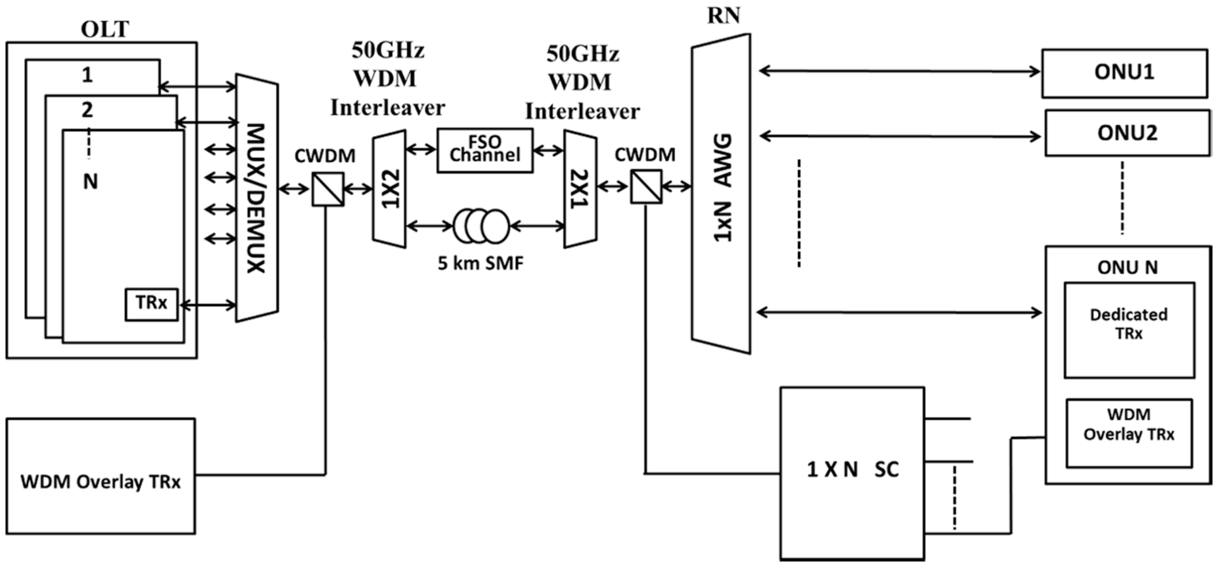

Fig. 1. Generalized proposed dual link based hybrid architecture.

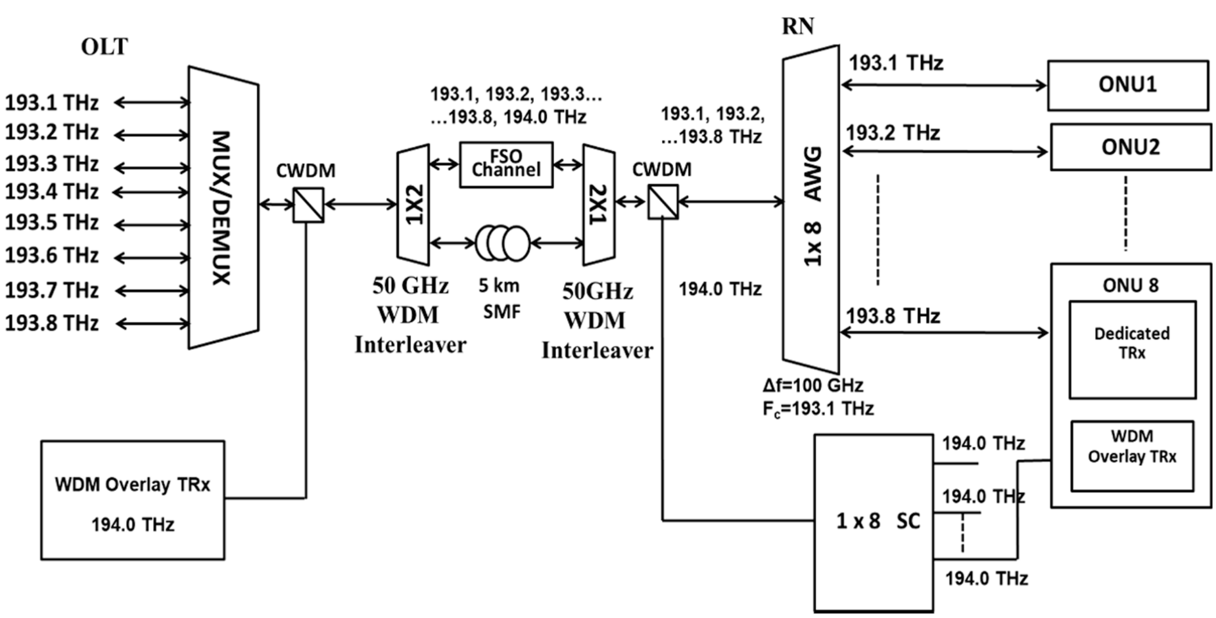

Fig. 2. FSO P2P and WDM overlay transmission.

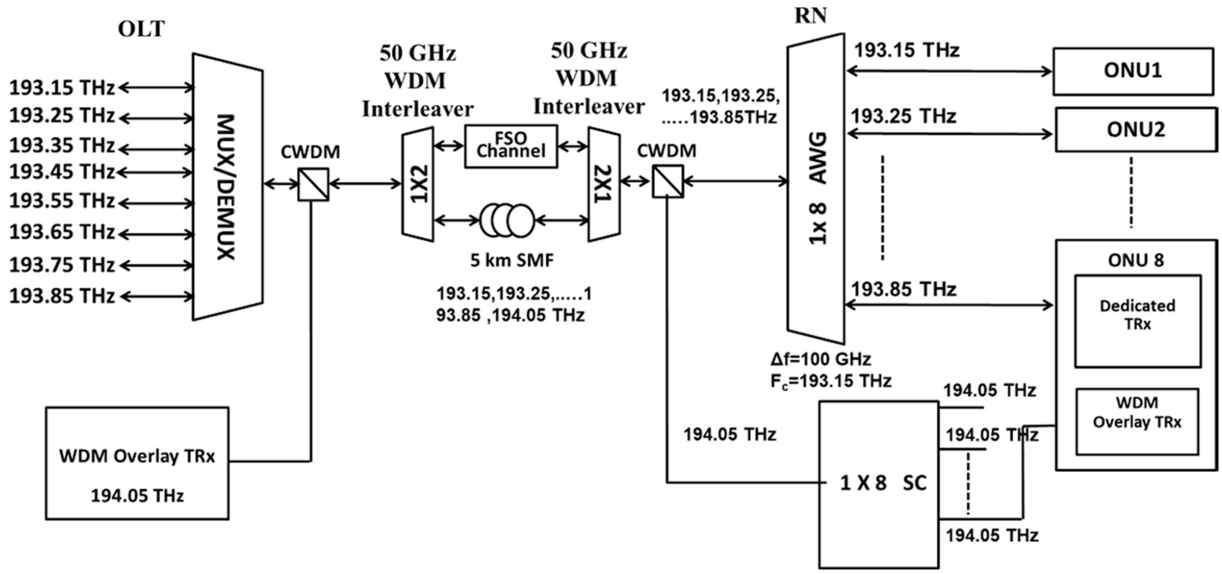

Fig. 3. SMF P2P and WDM overlay transmission.

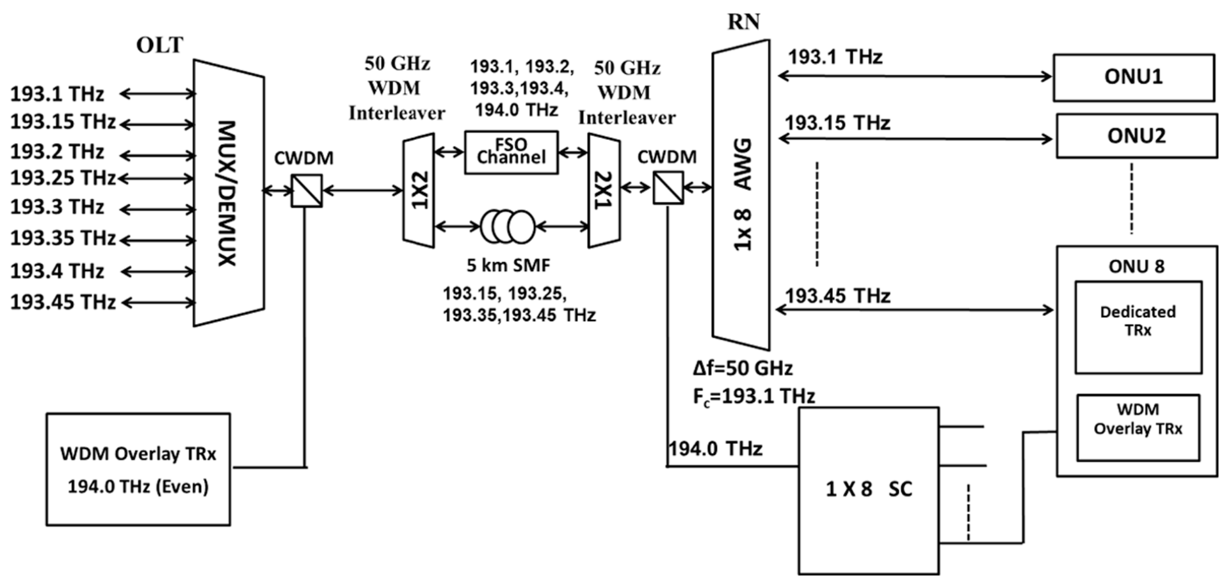

Fig. 4a. FSO/SMF Communication with FSO broadcasting.

well as cost compared to the FSO communication [6] i.e. the maintenance cost of FSO link is very less as the possibility of link failure for normal weather conditions is negligible. At the same time, the SMF link has comparatively larger maintenance costs as it has the fair chances of link failure due to the faults in the fiber due to digging or maintenance of roads etc. If there is a fault in the fiber then it needs to be repaired by permanent joints, which incur the cost and more insertion losses. Hybrid FSO/SMF link leverage the benefits of both FSO and SMF links and can be handled at moderate maintenance cost. The capital expenditure of fiber optic communication is almost five times more as compared to the FSO [7]. The transmission speed inside fiber optic communication is also small as compared to the FSO where transmission medium is air rather than glass [1,6]. Therefore, the combination of both FSO and fiber optic communication emerges as the best solution for providing reliable, low energy consumption, high speed, low maintenance, and secured internet services to the end-users.

Earlier, few cascaded architectures of optical fiber and FSO have proposed. In [8] Optical fiber is used as the backhaul of the network and FSO is used in the front haul for providing the services. However, the individual problems of both FSO and fiber optic links remain unsolved as both the technologies are connected in cascade rather parallel between the service provider and the end-user.

Authors have already proposed fiber optic-based various reliable and energy-efficient optical network architectures [9–13]. In this paper, we have integrated the fiber optic-based architecture with FSO and developed the hybrid FSO/fiber optic architecture that is capable of transmitting the data at 20GBPS up to 5 km distance through FSO or SMF paths just by tuning the transmitted wavelength appropriately. FSO link is preferred for clear weather conditions where environmental losses are considerably small. For unfavorable environmental conditions such as rain, fog, snow, haze, scintillation, the FSO path loss becomes significant and require very high power transmission. In these cases, fiber optic link is used without any hurdle of connectivity between transmitter and receiver with low transmitted powers. The proposed architecture is 100% more reliable against the failure of any link either FSO or SMF. The proposed architecture also has the capability of simultaneous transmission of dedicated point-to-point data and broadcasted data.

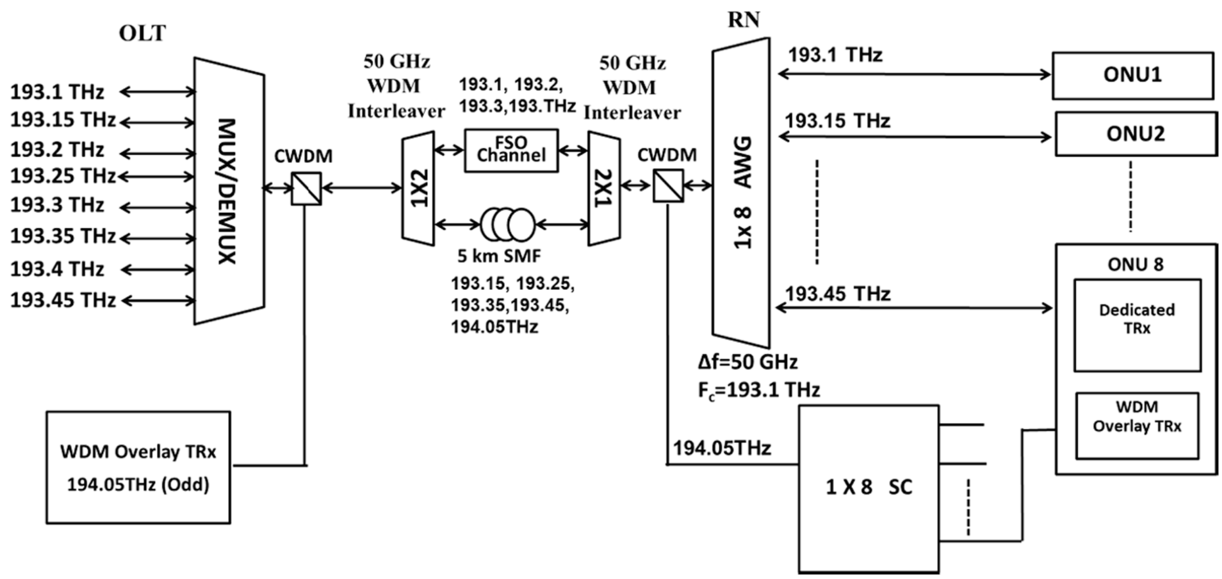

Fig. 4b. FSO/SMF Communication with SMF broadcasting.

Table 1
Various parameters of used components.

Components	Parameters
SMF	Dispersion:16.75 ps/nm/km, attenuation loss: 0.2 dB/km
AWG	Center Frequency: 193.1THz Spacing between two consecutive ports: 100 GHz, insertion loss: 5 dB
Power splitter 1X4/4X4	insertion loss: 7 dB
Power splitter/combiner 1x2	insertion loss: 3.5 dB
CWDM	Center frequency: 193.9THz, Wavelengths spacing between two ports: 20 nm, Insertion loss:0.5 dB
Circulator	Insertion loss:0.5 dB

Table 2
Losses for various weather situations and preferred link.

Weather Situation	Losses (dB/km) [6]	Preferred link
Clear	0.233	FSO
Low Haze	0.55	FSO
High Haze	2.37	FSO
Low Rain	6.27	SMF
Moderate Rain	9.64	SMF
High Rain	19.28	SMF

2. Proposed architecture & operation

The generalized schematic diagram of the proposed architecture is shown in Fig. 1. At the optical line terminal (OLT), there are N transceivers for sending and receiving the N wavelength signals. As per the requirement and available traffic load, these wavelength signals may be modulated at different data rates i.e. 1.25GBPS or 2.5GBPS. The transmitted wavelength signals are multiplexed and de-multiplexed by Nx1 MUX/DEMUX for downstream and upstream directions respectively. At OLT, one additional wavelength division multiplexed (WDM) overlay transceiver is used for transmission of broadcasted data in the downstream direction to all users available in the network. The WDM overlay wavelength is multiplexed and de-multiplexed by a coarse wavelength division multiplexer (CWDM). The wavelength range for two nearby bands of CWDM is 20 nm and the center frequency of CWDM is 193.9 THz. i.e. the frequencies arriving below 193.9THz within a range of 20 nm will come at one port and frequencies arriving above 193.9THz within a range of 20 nm will go to another port. There are two paths, FSO and SMF for transmission of the signals from OLT to the end-users and vice-versa. At the OLT side, these two paths are connected by a 1x2 50 GHz interleaver. The main purpose of the 50 GHz interleaver is to separate the even and odd multiple of 50 GHz wavelengths and transmitting at its two different ports and thereby at two different paths i.e. FSO and SMF. All the transmitted wavelengths that are even multiple of 50 GHz are provided one port and connected to the FSO link while odd multiple of 50 GHz wavelengths are provided at another port and connected to the SMF link. At another end of the link, these two paths are combined by the other 2x1 50 GHz interleaver. These combined wavelengths are given to CWDM to separate out WDM overlay wavelength if any and rest of the wavelengths are provided to 1xN AWG located at RN. This AWG separates out all the transmitted N wavelengths to different N ports and provides the services to the N ONUs located at the end-user. The separated WDM overlay wavelength is provided to the 1xN star coupler (SC) for broadcasting it to the entire ONUs available in the network.

FSO communication of the proposed architecture is depicted in Fig. 2. For the ease of understanding and simulation purposes, we have considered only 8 ONUs. Therefore at OLT, for point to point communication, we require 8 transceivers which are transmitting the even multiple of 50 GHz wavelengths i.e. 193.1THz, 193.2THz……193.8THz respectively. 50 GHz WDM interleaver allows these wavelengths to pass through the FSO channel and to reach to the 1x8 AWG. In this case, the center frequency (f_c) of AWG and wavelength spacing between its two consecutive ports (Δf) are considered 193.1THz and 100 GHz respectively. Due to the cyclic property of the AWG, it will separate out all the incoming wavelengths to its different ports. Wavelength 193.1THz will reach at port 1, wavelength 193.2THz will reach at port 2 and so on for a point to point communication i.e. 193.1THz, 193.2THz…..and 193.8THz will be received by ONU1, ONU2,……and ONU8 respectively. For broadcasting through the FSO link, the signal is transmitted at even multiple of 50 GHz wavelengths from the WDM overlay transmitter e.g. 194THz. At RN, CWDM diverts this wavelength towards the 1x8 SC and from where it is broadcasted to all eight ONUs and received by the WDM overlay TRx.

Just by tuning the transmitted wavelengths by 50 GHz i.e. 193.15 THz, 193.25THz, …0.193.85THz as depicted in Fig. 3, the proposed architecture is capable of transmitting the signal through SMF. In the case of abnormal environmental conditions such as rain, fog, snow, haze, scintillation, the FSO path loss may become significant and may

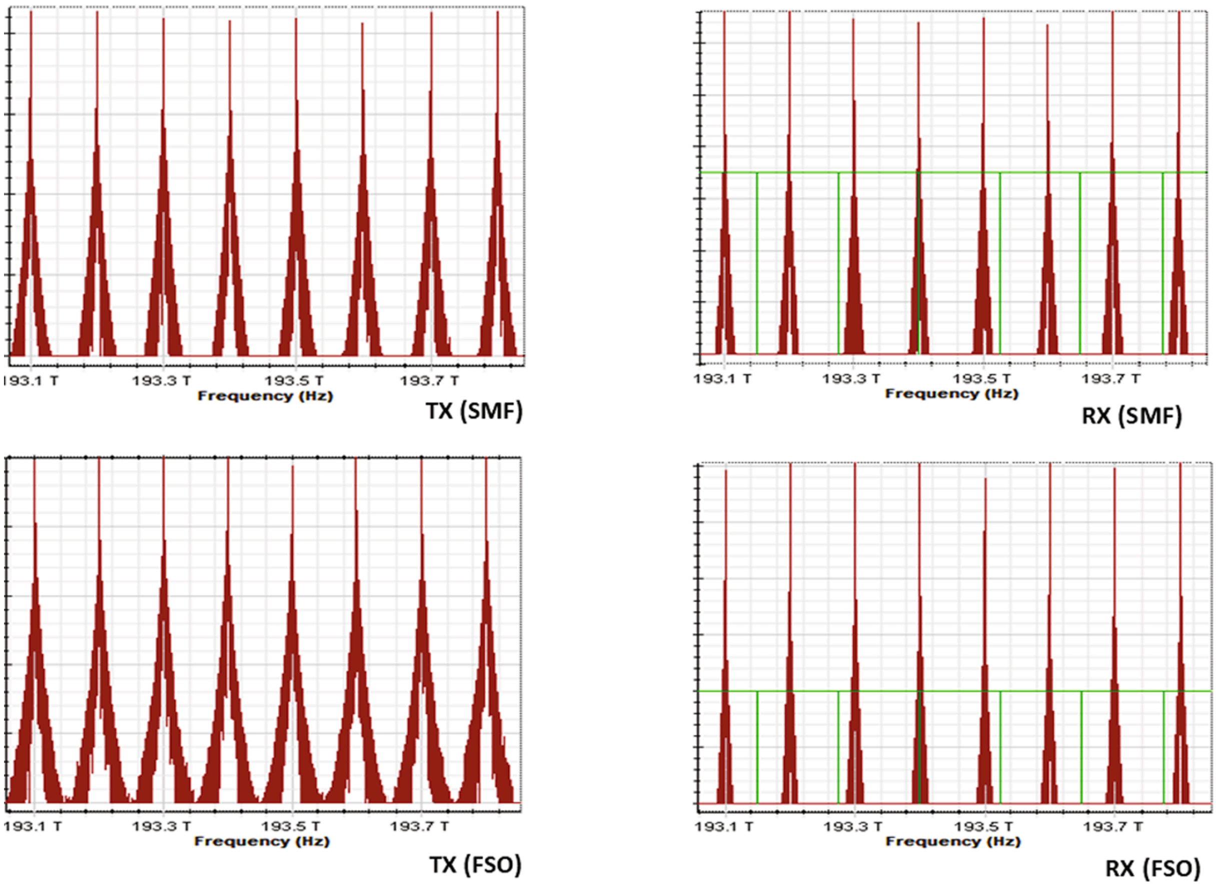

Fig. 5. Spectrum of transmitted and received signals.

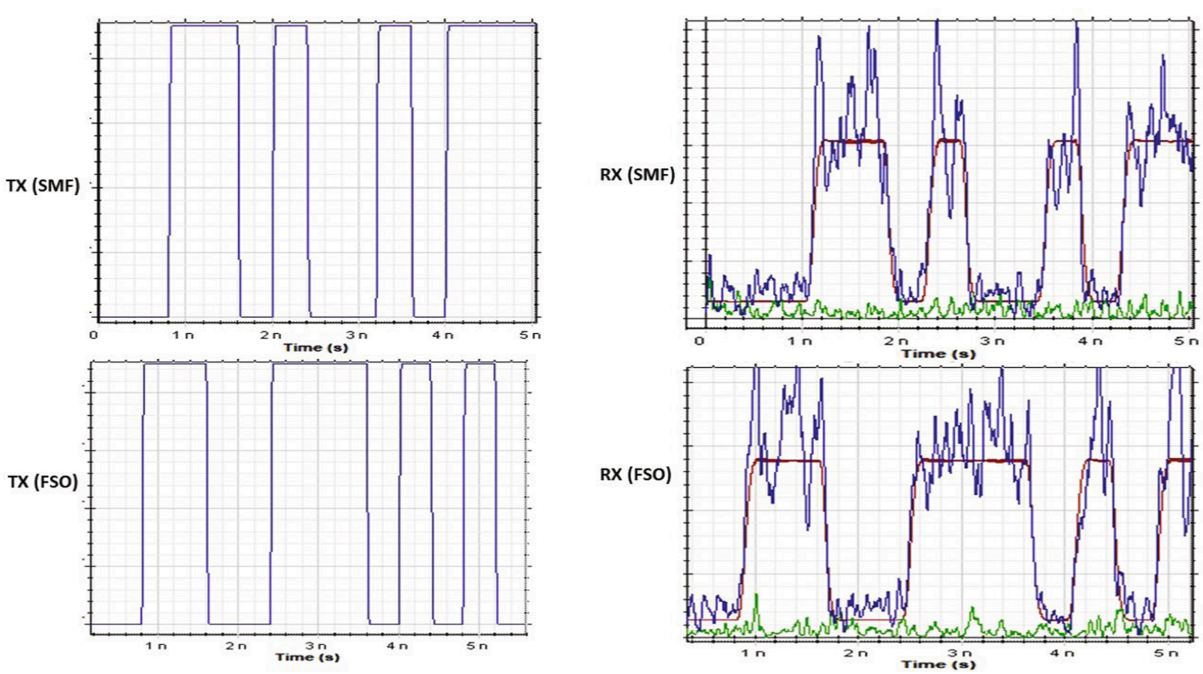

Fig. 6. Time-domain representation of transmitted and received signals at 2.5GBPS.

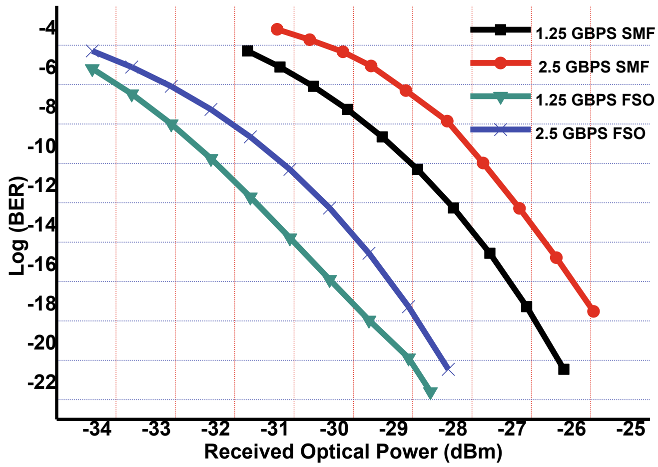

Fig. 7. BER performance for FSO and SMF.

not be able to transmit the data with low powers. In such cases, the SMF link may be preferred for transmitting the data energy efficiently. Since the transmitted wavelengths are the odd multiple of 50 GHz, the interleaver allows the entire wavelength signals to travel through the SMF link. The tuning of the transmitted wavelengths and link switching may be planned in much advanced, as very much accurate weather predictions are possible with the cutting-edge weather prediction technology. As for now, we are not working in this filed, however, we must say thanks to the people who are working rigorously day and night for their precise and accurate predictions. For transmission through SMF, f_c of AWG is tuned to 193.15THz, and Δf is kept the same as earlier i.e. 100 GHz. Due to the cyclic property of AWG, the wavelength 193.15THz will reach to port1 and ONU1, 193.25THz will reach to port2 and ONU2 and so on. For broadcasting of signal through the SMF, the WDM overlay transmitter is now tuned to 194.05THz. At RN, the WDM overlay wavelength is diverted towards 1x8 SC and broadcasted to all ONUs.

The proposed architecture also has the capability of transmitting the data from both the links FSO and SMF simultaneously to share the heavy traffic load. Also, for any of the link failures, the services may remain continued on another alternative link by properly tuning the transmitted wavelength without any additional efforts i.e. the proposed architecture is 100% more reliable against the link failure or heavy FSO losses in odd environmental conditions. For transmission of data through both the links, together with odd and even multiple of 50 GHz wavelengths are transmitted from the OLT. 1x2 interleaver will pass all even multiple of 50 GHz wavelengths to the FSO channel and all odd multiple of 50 GHz wavelength to the SMF as depicted in Fig. 4(a) and Fig. 4(b). For this particular case, the wavelength spacing of RN AWG is kept as 50 GHz and center frequency as 193.1THz. Due to the cyclic property of AWG, the wavelengths 193.1THz, 193.15THz, 193.2THz,……193.45THz will

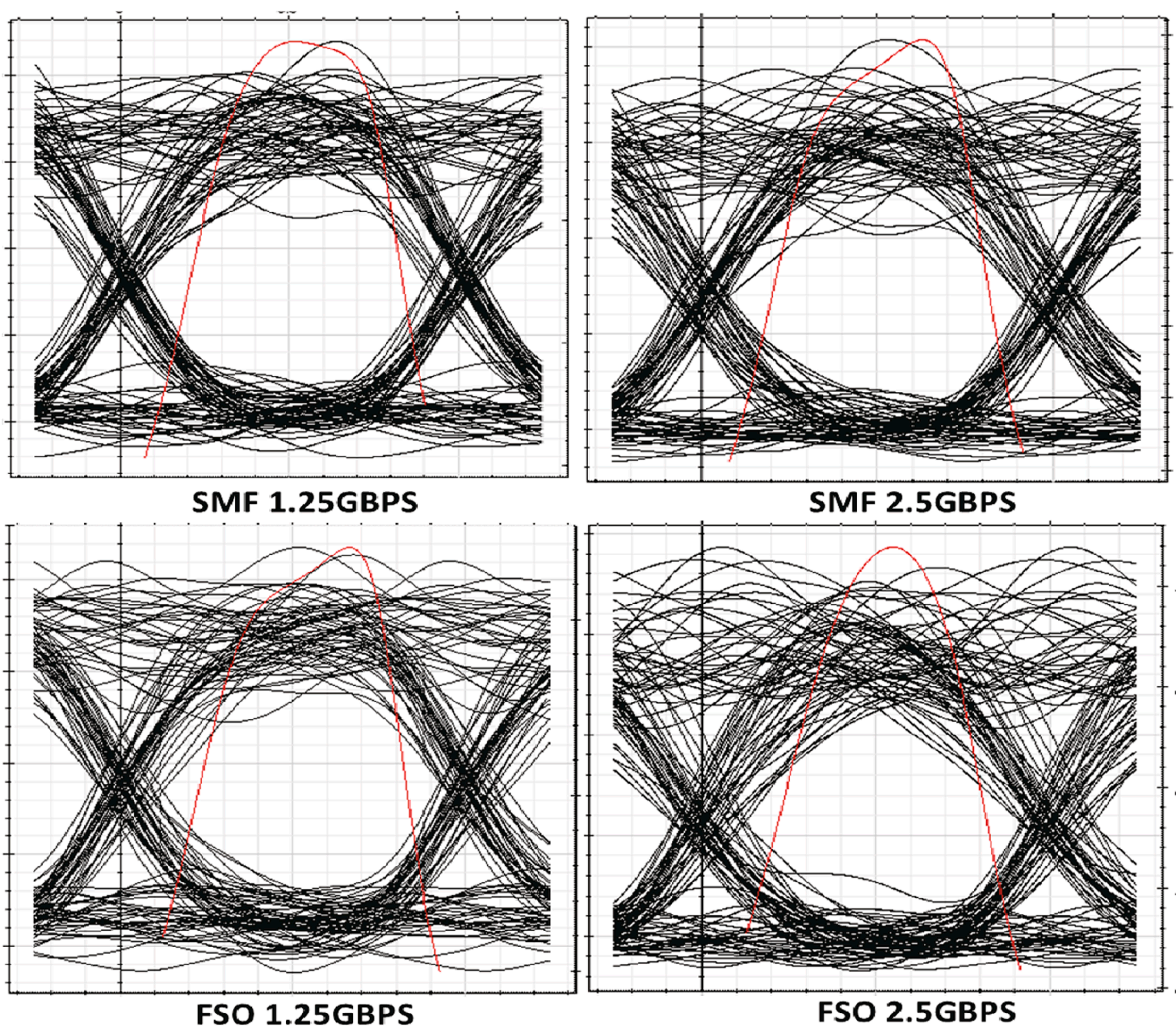

Fig. 8. EYE diagrams for FSO and SMF transmissions.

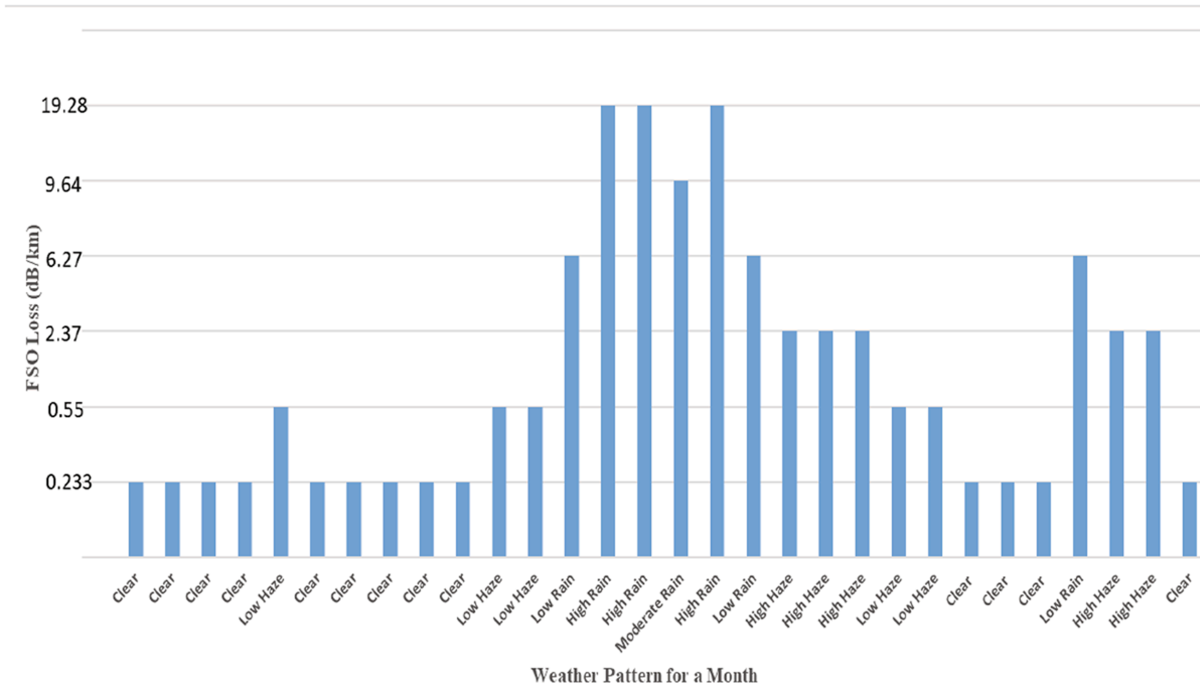

Fig. 9. 30 Days weather pattern.

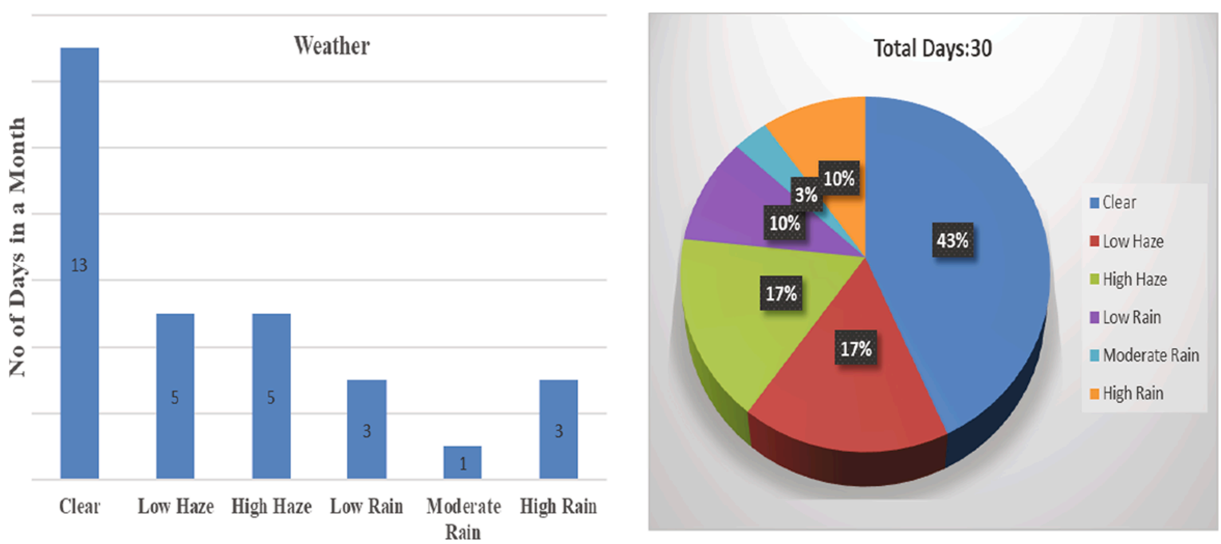

Fig. 10. (a) No. of days for various weather condition (b) Percentage of particular weather condition.

reach at ONU1, ONU2, ONU3……ONU8 respectively. WDM overlay broadcasting signal can be transmitted either of the links depending on the transmitted wavelength. If the transmitted wavelength is even multiple of 50 GHz then it will be transmitted through FSO link and called FSO broadcasting as depicted in Fig. 4 (a). If the transmitted wavelength is an odd multiple of 50 GHz then it will be transmitted through the SMF and called SMF broadcasting as depicted in Fig. 4 (b).

The various parameters of used components are given in Table 1

3. Results & discussions

The performance of the proposed architecture is verified with the help of simulation results through Optisystem 16.1. The losses in dB/km for the WDM-FSO link for different weather conditions are considered as given in Table 2 [6]. Also, the losses for SMF is considered approximately 0.2 dB/km. For the weather conditions for which the FSO losses are up to the manageable limit 2.37 dB/km, the FSO link may be utilized to transfer the data and for availing its various benefits. However, for odd environmental conditions, such as low rain, moderate rain or high rain, where losses are very high where FSO channel losses exceeds 2.37 dB/km, the SMF links are preferred for the energy-efficient transmission of data and avoiding the utilization of the number of costly repeaters in the link. In such cases, the SMF link allows transmitting the data with low transmitted powers and to reduce the significant energy consumption, which is a worldwide global issue for strengthening the information and communication technology (ICT) infrastructure and developing of smart cities.

The spectrum of the transmitted and received signals for FSO and SMF links is given in Fig. 5. The time-domain representation of the transmitted and received signals for FSO and SMF links is given in Fig. 6.

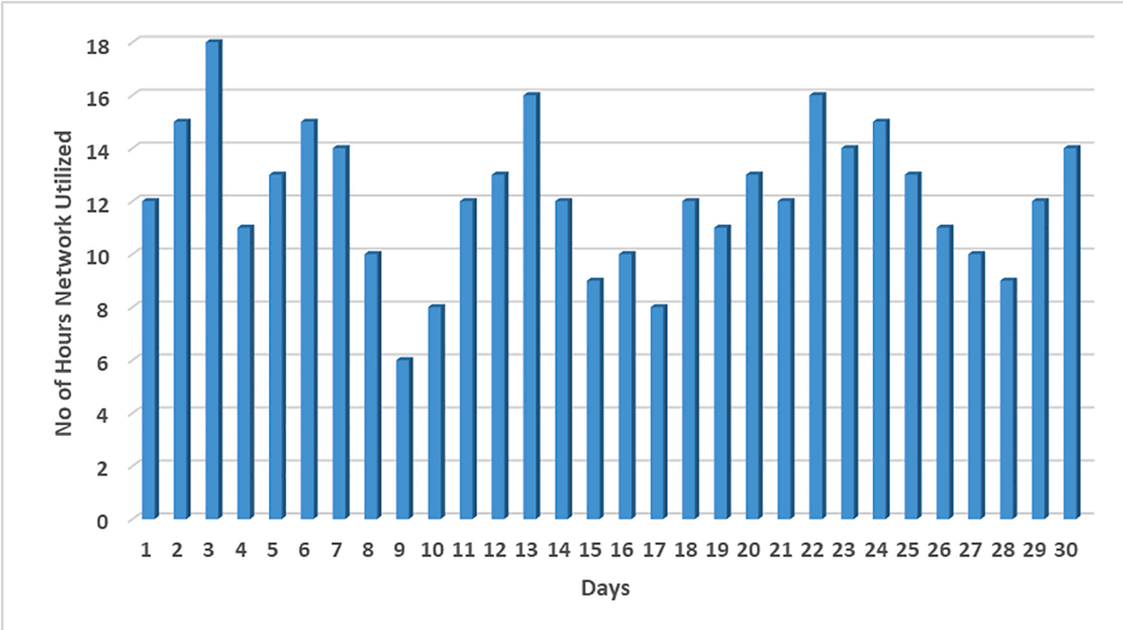

Fig. 11. Day-wise number of hours network utilization.

Table 3
Comparative analysis of Hybrid FSO/SMF link with pure FSO and pure SMF.

Parameters	Pure FSO Link	Pure SMF Link	Hybrid FSO/SMF link
Spectrum Licensing Requirement	No	Yes	Yes, for SMF Link
Energy Consumption	More	Less	Moderate
Installation Time	Low	High	Services can be started immediately by installing FSO link, SMF link may be installed simultaneously
Maintenance Cost	Low	High	Moderate
Reliability	Fair in clear weather conditions	Fair if faults are avoided during digging and maintenance of roads	Double as compared to individual FSO or SMF link and are suitable for all weather conditions

Both the figures indicate the proper reception of the transmitted signals through FSO and SMF links at another end.

The BER performance for various received powers for both the links FSO and SMF at 1.25GBPS and 2.5GBPS are indicated in Fig. 7. We have observed that for the Min [log (BER)] −9, the minimum required received powers are approximately −29.5dBm, −28dBm, -32.8dBm, and −31.8dBm for 1.25 GBPS SMF, 2.5 GBPS SMF, 1.25 GBPS FSO, and 2.5 GBPS FSO respectively. For normal weather conditions, the received powers are within the required receiver sensitivities. However, for rainy days, the FSO link requires extra-transmitted power as the path losses are more [1,6]. Performance of FSO link is slightly better than the SMF transmission and this is due to the various nonlinear effects such as Four-Wave Mixing (FWM), Cross-Phase Modulation (XPM) and Stimulated Raman Scattering (SRS) etc occurring inside the optical fiber [14,15]. Due to the nonlinear effects, the power penalty due to the SMF link is approximately 1.5 dB for the transition from 1.25 GBPS to 2.5 GBPS while it is only 1 dB for the FSO link. However, the performance for both SMF and FSO transmissions are within the acceptable limits for desired BER performance. The EYE diagrams for SMF and FSO transmissions at 1.25GBPS and 2.5GBPS are given in Fig. 8, which indicates the clear EYE opening without any overlapping of the transmitted data.

The main feature of the proposed architecture is that it is capable of transmitting the data through FSO as well as SMF. Ideally, we are using the FSO link to leverage its various benefits when the weather conditions are clear and link loss is up to only 2.37 dB. If the link losses are more due to adverse environmental conditions, the use of FSO is not advised, as it will consume more power. In such cases, just by tuning the transmitted wavelengths by 50 GHz, the signals can be transmitted through the SMF for which link losses are very low and are in the range of 0.2 dB/km. Therefore, the proposed architecture is useful for variable environmental conditions; we can transmit the data either through FSO or SMF link for reliable data transmission and reduce energy consumption. Just to check the energy efficiency of the proposed hybrid architecture, we have considered a representative weather pattern of a month. Sometimes it is very clear, sometimes it hazes or raining varying from low to high as given in Fig. 9. The total number of days for a particular weather condition is given in Fig. 10(a) and the percentage of the particular weather condition for the entire month is given in Fig. 10(b).

We have also considered the representative number of hours, each day for which network is utilized throughout the month as given in Fig. 11.

By considering the different weather conditions and the number of hours network utilization per day, we can calculate the energy saving of the proposed hybrid architecture. Out of 30 days, 7 days have low, moderate, or high rain and are not suitable for FSO communication since the link losses are high. By transmitting the data through FSO or SMF, depending on the weather conditions, we can save a significant amount of energy consumption and which is given by the following equations:-

$$E_{saving}(Month) = \sum_{d=1}^{30}\left[E(FSO)_d - E(SMF)_d\right] \quad (1)$$

$$E_{saving}(Month) = \sum_{d=1}^{30}\left[P(FSO)_d.h(FSO)_d - P(SMF)_d.h(SMF)_d\right] \quad (2)$$

$$E_{saving}(\%Month) = \frac{\sum_{d=1}^{30}\left[E(FSO)_d - E(SMF)_d\right.}{\sum_{d=1}^{30}\left[E(FSO)_d\right]} \quad (3)$$

$$E_{saving}(\%Month) = \frac{\sum_{d=1}^{30}\left[P(FSO)_d.h(FSO)_d - P(SMF)_d.h(SMF)_d\right]}{\sum_{d=1}^{30}\left[P(FSO)_d.h(FSO)_d\right]} \quad (4)$$

where $E_{saving}(Month)$ is the total energy saved in a month by the proposed architecture. *E(FSO)* and *E(SMF)* are the energy consumption for the FSO link and SMF link respectively for a day. *d* represents the day which is ranging from 1 to 30. *h(FSO)* and *h(SMF)* are the time duration (in hours) of a day for which FSO link and SMF link are utilized respectively.

Based on the Equations [1–4], and for the considered weather conditions and network utilization hours on different days of a month, approximately 14.46% of energy is saved by using the proposed hybrid link architecture as compared to the pure FSO link since FSO link requires approximately 5dBm-transmitted power while SMF link works satisfactorily with 0dBm-transmitted power. The energy-saving may be different for different weather conditions and different network utilizations. However, the proposed architecture gives us an idea to reduce the energy consumption of conventional FSO links.

The proposed architecture is 100% more reliable as compared to the normal FSO link as there are two active links and in case of failure of a working link, another link can be utilized just by transmitting the proper wavelengths. For the operational FSO link, if there are some LOS obstacles in clear weather conditions, then also we can transmit the signal on SMF. Similarly, for the operational SMF link, if there are some cuts or faults due to digging or maintenance of roads, then data transmission can be continued on the FSO link up to the recovery of the SMF link. However, in such a case, we may have to transmit slightly higher powers from the transmitter. i.e. there may be a tradeoff between the reliability and the energy saving.

Apart from the point-to-point downstream transmission, the proposed architecture also supports the broadcasting of the signal to all the available users in the network. A common signal need not required to be transmitted from the individual transmitters rather it is broadcasted from a WDM overlay transmitter. This feature further reduces the energy consumption, as the desired signal may be transmitted from the WDM overlay transmitter. Also in case of failure of any link between RN AWG and ONU, we can transmit the data on WDM overlay wavelength for that particular ONU and further increases the reliability. However, it will not provide the dedicated transmission but can be used for providing the services without any service disruption up to the recovery of a dedicated transmitter.

The various benefits and limitations of the proposed dual-link based hybrid optical network access architecture as compared to the conventional FSO and SMF links are summarized and given in Table 3 below.

4. Conclusion

A hybrid dual-link FSO/ SMF based optical access network architecture is proposed which is capable of transmitting the signals up to data rate 20GBPS for distance 5 km. The BER performance of the proposed architecture is verified with the simulation results for both the links separately, which is within the acceptable BER range. In unfavorable environmental conditions, such as rainy days, due to high path losses, the FSO link connectivity may be lost or require more transmitted powers, which is not desirable. In such cases, the proposed architecture is very useful and just by tuning the transmitted wavelengths by 50 GHz, the transmission of data is switched from the FSO link to the SMF link. The proposed architecture provides reliability against link failure and reduces energy consumption significantly. For the considered representative weather conditions and network utilization hours, approximately 14.46% of energy consumption is reduced as compared to the simple FSO link. The architecture supports the WDM overlay transmission for broadcasting any data. The proposed architecture is also reliable against the failure of any link between RN AWG and ONUs by providing the services at broadcasted wavelength. Hybrid architecture avails the benefits of both the links FSO as well as SMF and strengthens the ICT infrastructure and very useful for providing the services to the next generation networks.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The corresponding author would like to thank the THz Communication and Photonics Lab, Department of ECE, Malaviya National Institute of Technology, Jaipur for providing the simulation facilities. The author (Bostjan Batagelj) also acknowledge the financial support from the Slovenian Research Agency (research core funding No. P2-0246) Information and Communications Technologies for Quality of Life (ICT4QoL) and European Cooperation in Science and Technology (COST) Action CA19111, European Network on Future Generation Optical Wireless Communication Technologies.

References

[1] A.G. Alkholidi, K.S. Altowij, Free Space Optical Communications — Theory and Practices, Contemporary Issues in Wireless Communications, Mutamed Khatib, IntechOpen. doi: 10.5772/58884 (November 26th 2014).
[2] V.W.S. Chan, Free-space optical communications, J. Lightwave Technol. 24 (12) (2006) 4750–4762.
[3] M. Ijaz, Z. Ghassemlooy, J. Pesek, O. Fiser, H. Le Minh, E. Bentley, Modeling of fog and smoke attenuation in free space optical communications link under controlled laboratory conditions, J. Lightwave Technol. 31 (11) (2013) 1720–1726.
[4] A. Zabidi, et al., Investigating of rain attenuation impact on Free Space Optics propagation in tropical region. 1-6. 10.1109/ICOM.2011.5937121. (2011).
[5] S.A. Al-Gailani, A.B. Mohammad, R.Q. Shaddad, Enhancement of free space optical link in heavy rain attenuation using multiple beam concept, Optik 124 (21) (2013) 4798–4801, https://doi.org/10.1016/j.ijleo.2013.01.098.
[6] A. Malik, P. Singh, Free space optics: current applications and future challenge, Int. J. Optics (2015), https://doi.org/10.1155/2015/945483.
[7] H.A. Willebrand, B.S. Ghuman, Fiber optics without fiber, IEEE Spectr. 38 (8) (2001) 40–45, https://doi.org/10.1109/6.938713.
[8] Pham, Tu V. M., Thang V. Nguyen, Nga T. T. Nguyen, Thu A. Pham, Hien T. T. Pham, Ngoc T. Dang. Performance analysis of hybrid fiber/FSO backhaul downlink over WDM-PON impaired by four-wave mixing, J. Optical Commun. 41, 1: 91-98, doi: 10.1515/joc-2017-0127.
[9] A.K. Garg, A.A. Madavi, V. Janyani, Energy efficient flexible hybrid wavelength division multiplexing-time division multiplexing passive optical network with pay as you grow deployment, Opt. Eng 56 (2) (2017) 026119, https://doi.org/10.1117/1.OE.56.2.026119.
[10] A.K. Garg, V. Janyani, Adaptive bandwidth mechanism using dual rate OLT for energy efficient WDM–TDM passive optical network, Telecommun. Syst. 66 (4) (2017) 657–670, https://doi.org/10.1007/s11235-017-0316-1.
[11] A.K. Garg, V. Janyani, Resilient, bandwidth scalable and energy efficient hybrid PON architecture, Telecommun. Syst. 67 (4) (2018) 687–698, https://doi.org/10.1007/s11235-017-0369-1.
[12] A.K. Garg, V. Janyani, G. Singh, T. Ismail, H. Selmy, Dedicated and broadcasting downstream transmission with energy-efficient and latency-aware ONU interconnection in WDM-PON for smart cities, Opt. Fiber Technol. 52 (2019) 101949, https://doi.org/10.1016/j.yofte.2019.101949.
[13] A. Kumar Garg, V. Janyani, B. Batagelj, Ring based latency-aware and energy-efficient Hybrid WDM TDM-PON with ODN interconnection capability for smart cities, Opt. Fiber Technol. 58 (2020) 102242, https://doi.org/10.1016/j.yofte.2020.102242.
[14] T. Sabapathi, R. Poovitha, Combating the effect of nonlinearities in DWDM system, 2017 4th International Conference on Electronics and Communication Systems (ICECS), Coimbatore, 2017, pp. 38–42, doi: 10.1109/ECS.2017.8067876.
[15] A.E. Morra, K. Ahmed, S. Hranilovic, Impact of fiber nonlinearity on 5G backhauling via mixed FSO/fiber network, IEEE Access 5 (2017) 19942–19950, https://doi.org/10.1109/ACCESS.2017.2753178.

Amit Kumar Garg is an Assistant Professor in the Dept. of Electronics & Comm. Engineering, Indian Institute of Information Technology, Kota, India (An Institute of National Importance under an Act of Parliament). He obtained his Ph.D. from the Department of Electronics and Communication Engineering at Malaviya National Institute of Technology (MNIT), Jaipur, India in 2018. He received B.E. and M.Tech. in ECE from the University of Rajasthan and MNIT Jaipur in 2009 and 2013 respectively. His current research interest includes fiber optics and photonics including energy-efficient and latency-aware optical

access networks and high-speed gigabit passive optical networks. He is an active and early career member of SPIE and OSA. He is the recipient of the SPIE officer travel grant.

Vijay Janyani obtained his Bachelor's and Master's degrees in engineering from MNIT Jaipur (erstwhile MREC Jaipur), and Ph.D. Degree from UK under Commonwealth Scholarship Plan. He has received various honours such as AICTE Career Award for Young Teachers, Derrick Kirk Prize for Excellence in Research. He has completed important collaborative projects, both at National and International levels. He has already guided seven PhDs, and four are underway. He is present with the Department of ECE at MNIT Jaipur. His areas of interest include optical communication, photonics and numerical modeling.

Bostjan Batagelj received his Ph.D. from the University of Ljubljana in 2003 for work on optical-fiber non-linearity measurements by four-wave mixing. He is currently an associate professor at the University of Ljubljana, Faculty of Electrical Engineering. His current research interests are in areas of next-generation optical access networks, optical technology-based timing systems and microwave photonics. He has authored or co-authored over 250 technical and scientific publications and is named as an inventor on ten patents. He was a co-founder of two start-up companies in the field of microwave and optical technologies.

N. H. Zainol Abidin received her Bachelor of Engineering (Electrical and Electronics Engineering) from Vanderbilt University, Nashville, USA in 2012. Upon graduation, she was immediately hired as a Radio Frequency Engineer by Digi Telecommunications Sdn. Bhd. In 2013, she was awarded the Erasmus Mundus Mobility Scholarship where she did her research attachment with the Communications Lab of Northumbria University, Newcastle, UK for 10 months. Within the same year, she received the Academic Trainee Fellowship under Universiti Putra Malaysia (UPM). She completed her Ph.D degree in Photonics Engineering in the year 2017. Dr. Zainol Abidin is currently a Senior Lecturer in UPM. She is affiliated with IEEE Young Professionals Malaysia and is leading the Optical Society (OSA) Student Chapter in UPM. Her research interests include ultrafast photonics, fiber lasers, and fiber sensors.

M.H. Abu Bakar received his Ph.D. degree in Photonics and Fiber Optic Systems Engineering from Universiti Putra Malaysia (UPM) in 2012. He is now an Associate Professor with UPM. He is a Senior Member of the IEEE Photonics Society and The Optical Society (OSA). His current research interests include optical communication devices and sensors.