CommIT Journal 18(1), 17–27, 2024

Simulating Free-Space Optical Communications to Support a Li-Fi Access Network in a Smart City Concept

Ucuk Darusalam[1]*, Novi Dian Nathasia[2], Muhammad Zarlis[3], and Purnomo Sidi Priambodo[4]
[1]Informatics Department, Faculty of Information Communications Technology, Universitas Nasional
Jakarta, Indonesia 12520
[1,2]Informatics Department, Universitas Siber Asia
Jakarta, Indonesia 12550
[2]Information System Department, Faculty of Information Communications Technology,
Universitas Nasional
Jakarta, Indonesia 12520
[3]Information Systems Management Department, BINUS Graduate Program – Master of Information
Systems Management, Bina Nusantara University
Jakarta, Indonesia 11480
[4]Electrical Engineering Department, Faculty of Engineering, Universitas Indonesia
Depok, Indonesia 16424
Email: [1]ucuk.darusalam@civitas.unas.ac.id, [1]ucukdarusalam@exe.unsia.ac.id,
[2]novidian@civitas.unas.ac.id, [3]muhammad.zarlis@binus.ac.id, [4]pspriambodo@gmail.com

***Abstract*—Smart city development has grown rapidly in the decades since 4G and 5G technologies have been released. Moreover, a highly reliable network is required to support the Internet of Things (IoT) and mobile access within a city. Light Fidelity (Li-Fi) technology can provide huge bitrate transmission and high-speed communications. In the research, a backbone based on Free-Space Optical (FSO) communication (FSO) is designed through simulation to provide a Li-Fi access network with a high capacity data rate. The originality of the proposed method is the implementation of double filtering techniques, which gives an advantage when forwarding the signal to a node and improves the quality of the signal received by the Li-Fi. The FSO as the Optical Relaying Network (ORN) is designed with a configuration of 12 channels of Dense Wavelength Division Multiplexing (DWDM) amplified by optical amplifiers in the transmitter and receiver. The signal output is filtered by a Fiber Bragg Grating (FBG) and a Gaussian filter. In the simulation, the ORN has node spacing in the range of 500 m to 2,000 m. Then, the data transmission rate at 120 Gbps is provided by the implementation of DWDM channels to serve as an access network. From the simulation, the FSO backbone can optimally deliver highly reliable Li-Fi access networks. When the nodes are spaced in a 500–2,000 m range, the Bit-Error-Rate (BER) performance is produced at the order of 10^{-6}.**

Received: Aug. 29, 2023; received in revised form: Jan. 09, 2024; accepted: Jan. 10, 2024; available online: April 05, 2024.
*Corresponding Author

***Index Terms*—Free-Space Optical (FSO) Communications, Li-Fi Access Network, Smart City**

I. INTRODUCTION

THE demand to develop a smart city has grown rapidly [1–3]. It is possible to develop a smart city intensively because governmental awareness about the issues of a green environment, easy living, as well as modern and reliable online services has increased [4–6]. Some governments have declared their awareness of the green environment by implementing a smart city concept as their advanced program. They realize this through the superstructure approach, which entails making regulations to support smart city development. It means that regulation is the fundamental act of governance needed to implement a reliable smart city.

A smart city is a breakthrough program that can enhance citizens' quality of life. It can improve the productivity of citizens who are predominantly active online or on the Internet rather than through physical activity. It also can improve the efficiency of the government in providing many administrative services, such as license submission, smart governance system, and others [7]. The activity of the economy has also changed into digital transactions or the "digital economy" [8]. The digital economy is growing quickly worldwide and has become a new way for people to work from home. Similarly, education has already moved to online classrooms and the use of a pedagogical method that combines offline and online classes or blended or hybrid learning [9]. The mobility of citizens in a smart city is also trending toward changes to electrically smart vehicles that provide energy efficiency and timing accuracy to serve passengers in a crowded city [10].

Basically, smart city development is based upon the availability of physical network infrastructure, government regulation support, high speed and high data-transmission-rate systems (4G and 5G), product innovation on smart digital platforms (smart home apps), and global network communications [11, 12]. When those factors are fulfilled, a smart city concept can be implemented to create a modern living environment with the benefits of high security, joyful and easy living, and clean energy consumption. A smart city also implements the Internet of Things (IoT) technology, where all things that are related to human activities are connected to the network [13, 14]. Thus, every citizen in a city can get information and control all the things that have been integrated into the networks through a smart application, such as smart home apps. However, these ideals face the major problem of the Internet connection to reach users or things across the "last mile". Because Wi-Fi connects with users and things across the last mile, the data transmission rate is limited to 600 Mbps for a frequency of 2.4 GHz and 1.3 Gbps for a frequency of 5 GHz [15, 16]. Meanwhile, a smart city concept must implement an unlimited connection to all users and things that are integrated into the IoT. However, Wi-Fi has a limited payload and data transmission rate.

Light Fidelity or Li-Fi has recently developed worldwide because it has many benefits, including free license, speed on the order of the speed of light, freedom from Electromagnetic Interference (EMI), high bandwidth, broad spectrum of light, high security, and low-cost deployment [17–20]. Li-Fi is an access network that utilizes light transmission. Light generated by a Light Emitting Diode (LED) travels into the free medium, such as open air in a closed or open environment. Li-Fi has the potential to be implemented as the last-mile access network for users and things [17, 18]. Li-Fi has been designed to carry data at a transmission rate on the scale of 100 Gbps and can cover an area with a radius of 20 m [19]. Thus, smart city development can utilize Li-Fi technology as the main infrastructure of the access network and serve as the last-mile interface network to reach users or things throughout a city [20].

Free-Space Optical (FSO) communications have also been developed intensively in the last two decades [21–24]. FSO is an optical communications platform that utilizes laser light as the carrier to penetrate the free-space medium, such as open air. The virtues of FSO are almost the same as those of Li-Fi technology, but its data transmission rate is on the scale of Tbps because it uses a high-power, monochromatic laser as the light source. FSO can be implemented as a backbone network to support high bitrate transmission in the Li-Fi access network in a smart city. The prospect of integrating FSO and Li-Fi as all-optical access networks will provide high speed and bitrate transmission [25–27].

Li-Fi technology offers high-speed access at a transmission rate of 10 Mbps to 80 Mbps. Thus, it needs access to a data distribution "highway" or "backbone". The FSO backbone can be designed to be a flexible connection that does not have to follow the physical infrastructure of the city, such as open roads or open public facilities. The FSO configuration can be implemented in the form of Optical Relaying Networks (ORN). By integrating Li-Fi over FSO, channel interference can be avoided. Wireless technology based on microwave frequencies does not provide this benefit. Thus, Li-Fi over FSO offers secure and high-reliability connections. The integration of Li-Fi over FSO has achieved a data transmission rate on the scale of 640 Gbps generated from eight orthogonal channels with good performance [27].

In previous research [26], an FSO system is simulated with optical code modulation access to improve the performance of a Li-Fi access network. It successfully demonstrates a data transmission rate on a scale of 10 Gbps. In another research [28], an FSO system is designed as the access network on the scale of 50 Mbps for Wi-Fi to connect to the IoT. Also, an FSO system is outlined using the technique of Blind Source Separation (BSS), which is used to extract the original information from the mixed signals [29]. Thus, FSO can be designed in a MIMO transmission scheme to accommodate the IoT or mobile user connection. The implementation and future challenge development aspects of Li-Fi are reviewed [30]. Li-Fi is used for multi-user access with a high data transmission rate by using Non-Orthogonal Multiple Access (NOMA) techniques.

In the research, an FSO configuration scheme designed as the highway access network or backbone in a smart city concept is investigated through simulation. The research is also the continuation of work on the development of FSO as the ORN to provide a last-mile access network for IoT and users [24, 31–34]. The implementation of FSO technology as the backbone access network is quite challenging because

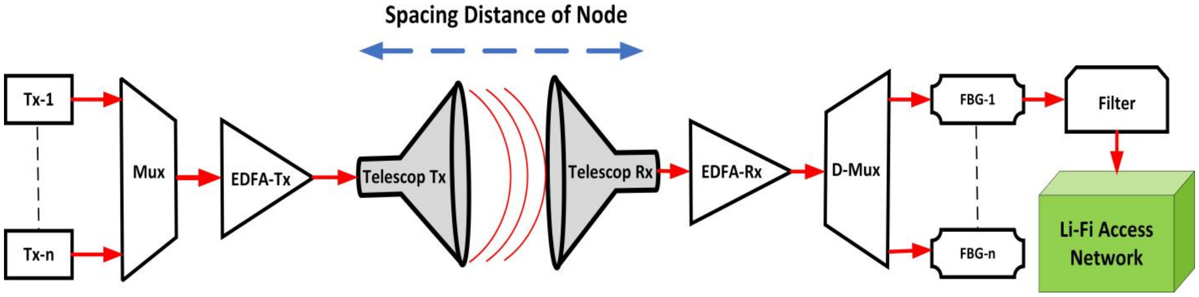


Fig. 1. The Wavelength Division Multiplexing (WDM) on the backbone Free-Space Optical (FSO) network for distributed Li-Fi access implementing 12 channels, where the node spacing distance constitutes the relaying network.

the open air in a city is very different from the open air outside a city. The major problem is avoiding a long transmission range to achieve high-reliability connections. It is possible to configure FSO over short distances by considering the terrain of the physical city, which consists of many high-rise buildings.

In the research, FSO is designed for a short transmission range to serve a distributed Li-Fi access network. In the simulation, an FSO backbone access network is designed to carry a payload data transmission rate on the scale of 120 Gbps. The total distance of the backbone is on the order of 10 km because the physical area of a city is limited by suburban surroundings. The FSO spacing distances are designed to vary between 1 and 2 km because high-rise building obstacles are the major problem when extending long-range transmissions. Open air as the medium of optical transmission is also quite challenging. In a modern city, traffic and other heat sources cause thermal fluctuations, leading to severe performance degradation.

The novelty proposed in the research is that the FSO backbone is designed in a Dense Wavelength Division Multiplexing (DWDM) system that implements double filtering techniques. The filtering process is achieved by implementing Fiber Bragg Grating (FBG) and Gaussian filters. An FBG has the main role of distributing a selected channel into a Li-Fi access network. During the distribution, the FBG can function as a filter to suppress noise modulations by setting the bandwidth of the signal that is allowed to pass through. Furthermore, the selected channel from the FBG is then received by the Gaussian filter in front of the Photodetector (PD). The Gaussian filter optimizes the noise suppression to produce a signal with high performance. The Wavelength Division Multiplexing (WDM) on the FSO is designed as a high-rate transmission on the scale of 120 Gbps, considering its function as the backbone access network. The benefits of DWDM on FSO are that instead of merely providing high data transmission rates, it can also avoid inter-channel crosstalk because the spacing distance between Li-Fi access points is very close or short. Thus, by that proposed method, the backbone access network can achieve high-reliability connections to serve distributed Li-Fi access networks throughout a smart city.

II. Research Method

The FSO simulation is performed using Optisystem software. The DWDM design on the FSO is shown in Fig. 1. The main components, instruments, and channels are shown in Tables I–IV. DWDM channels are provided by several laser transmitters (Tx-1–Tx-n). The Tx-n output is combined into a Multiplexer (Mux) into a single Single-Mode Fiber (SMF) transmission. The Mux output is coupled into the Erbium-Doped Fiber Amplifier (EDFA-Tx). The EDFA amplifies all DWDM channels to achieve high signal gain. Thus, the output power from the EDFA-Tx is high to achieve enough power to penetrate the open air of a city environment.

The light output from the EDFA-Tx is then transmitted by the collimator of the telescope Tx. The output of the telescope Tx is an optical beam of light that is transmitted through the open air to the telescope of the receiver (Rx). The optical propagation is received by the telescope Rx and coupled into the EDFA-Rx because the optical signal performs free propagation in the open air, which attenuates the beam light. The EDFA-Rx amplifies the weak signal and delivers it into a De-Multiplexer (De-Mux) to split multi-channels into single channels. Every channel is filtered by the FBG to produce a signal with a minimum of the noise modulation that is induced during optical propagation in the open air. The main function of the FBG is to filter noise and make sure that only specific allowed channels will go to the Li-Fi access network. Instead of selecting the channel, the FBG also ensures low noise suppression and minimizes noise figures by the EDFA. The FBG output is then forwarded into a spatial filter, such as a Gaussian filter [35]. The spatial

TABLE I
The Dense Wavelength Division Multiplexing (DWDM) Consisting of 12 Channels Ranging from a Wavelength of 1557.36 nm to 1548.51 nm.

No.	Channel	Frequency (Hz)	Wavelength (nm)
1	25	192.5	1557.36
2	26	192.6	1556.56
3	27	192.7	1555.75
4	28	192.8	1554.94
5	29	192.9	1554.13
6	30	193.0	1553.33
7	31	193.1	1552.52
8	32	193.2	1551.72
9	33	193.3	1550.92
10	34	193.4	1550.12
11	35	193.5	1549.31
12	36	193.6	1548.51

TABLE II
The Parameters of the Main Wavelength Division Multiplexing (WDM) Component on the Free-Space Optical (FSO) Used in the Optisystem Simulation.

No.	Component	Output
1	Laser Tx	0 dBm
2	Mux	10 to 1
3	D-Mux	1 to 10
4	EDFA-Tx	5–30 dBm
5	EDFA-Rx	5–15 dBm
6	FBG	1 selected channel

Note: Tx: Transmitter, Mux: Multiplexer, De-Mux: De-Multiplexer, EDFA-Tx: Erbium-Doped Fiber Amplifier - Transmitter, EDFA-Rx: Erbium-Doped Fiber Amplifier - Receiver, and FBG: Fiber Bragg Grating.

TABLE III
The Optical Properties Setup for the Telescopes in the Free-Space Optical (FSO) Transmitter and Receiver.

No.	Component	Output
1	Lens diameter of telescope Tx	5 cm
2	Lens diameter of telescope Rx	20 cm
3	Beam divergence	2 mrad

Note: Tx: Transmitter and Rx: Receiver.

TABLE IV
The Main Instruments Used in the Free-Space Optical (FSO) Network with Wavelength Division Multiplexing (WDM) Simulation to Measure the Performance of the Signal.

No.	Instrument	Position
1	Optical power meter	Tx and Rx
2	Optical spectrum analyzer	Tx and Rx
3	BER-meter	Tx and Rx
4	WDM analyzer	Tx and Rx

Note: BER: Bit-Error-Rate, WDM: Wavelength Division Multiplexing, Tx: Transmitter, and Rx: Receiver.

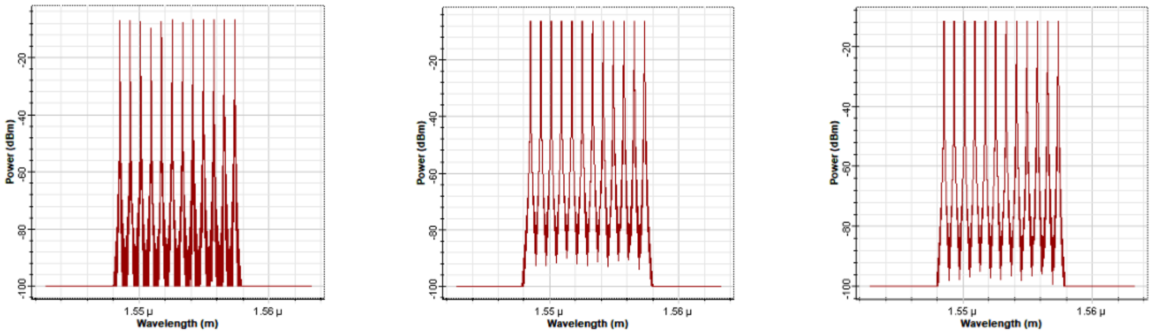
filter suppresses noise around the center wavelength or channel. The output signal of the optical filter reaches out to the Li-Fi receiver, which is a photodiode (PD). The PD output is filtered out by an electronic filter, such as a low-pass filter, to suppress the electrical signal noise [35].

Table I shows the frequency and wavelength for the 12 channels based on the ITU G.694.1 grid channel. The simulation uses 100 GHz spacing for a standard DWDM region from 1548.51 nm to 1557.36 nm within the C-band spectrum. In the simulation, each channel is designed to have a bitrate transmission capacity of 10 Gbps with Non-Return to Zero (NRZ) modulation. The total bitrate transmission in one node with 12 channels is 120 Gbps. Thus, each channel (25th–36th) can support the high-bitrate payload required to transmit to the Li-Fi access network.

In Tables II and III, the main optoelectronic and optical components used in the simulation are shown. The main function of the telescope Tx is to perform collimation of the beam light into a diameter of 5 cm. Then, the beam light is transmitted through the open air to the telescope Rx. The diameter of telescope Rx is 20 cm, and the remaining beam divergence is not high. Thus, the 20 cm diameter of telescope Rx is sufficient to receive the beam light from the optical propagation in the open air. The simulation is performed using Optisystem software, where the main factor of turbulence in the open air of a city can be assumed to be very low as long as the optical propagation is less than 100 m above the ground. Thus, any variation of the refraction index can be neglected. The only factor that influences the optical propagation from telescope Tx to Rx is the attenuation factor caused by dust, air pollution, and water vapor. Also, because the height of optical propagation is low or near the ground, the phenomena of beam wandering can be neglected in the simulation [36].

Table IV lists four main instruments used to measure the optical and electrical signal characteristics in terms of power, signal spectral, gain, noise, eye diagram, and quality factor. The parameters to be measured in the simulation are decibel, Signal-to-Noise Ratio (SNR), and Bit-Error-Rate (BER). In the simulation, the node spacing range is designed in the order of 500 m to 2.5 km. That spacing distance is designed by considering that the FSO can deliver and receive data to and from the Li-Fi access network across a very short range. Thus, the Li-Fi network can function as the last-mile access point to reach the user in a nearest-neighbor distribution, such as a public indoor room.

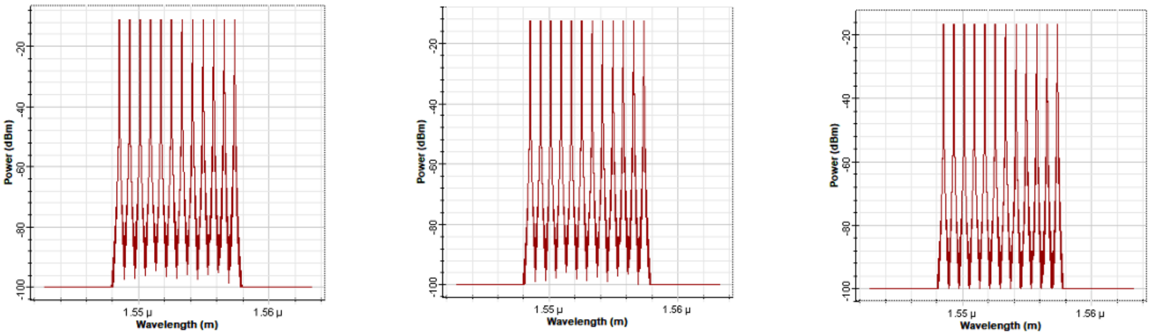
Based on Fig. 1 and Tables I–III, the integration of Li-Fi over FSO is designed to provide a high bitrate transmission on the scale of 120 Gbps through 12 DWDM channels. Also, implementing double filtering techniques via FBG and Gaussian filters can optimize



(a) SNR from the EDFA-Tx at the power output of 5 dBm.

(b) SNR from the EDFA-Rx at the power output of 5 dBm where the node spacing distance is 500 m.

(c) SNR from the EDFA-Rx at the power output of 5 dBm and a node spacing distance of 1,000 m.



(d) SNR from the EDFA-Rx at the power output of 5 dBm and a node spacing distance of 1,500 m.

(e) SNR from the EDFA-Rx at the power output of 10 dBm and a node spacing distance of 2,000 m.

(f) SNR from the EDFA-Rx at the power output of 15 dBm and a node spacing distance of 2,500 m.

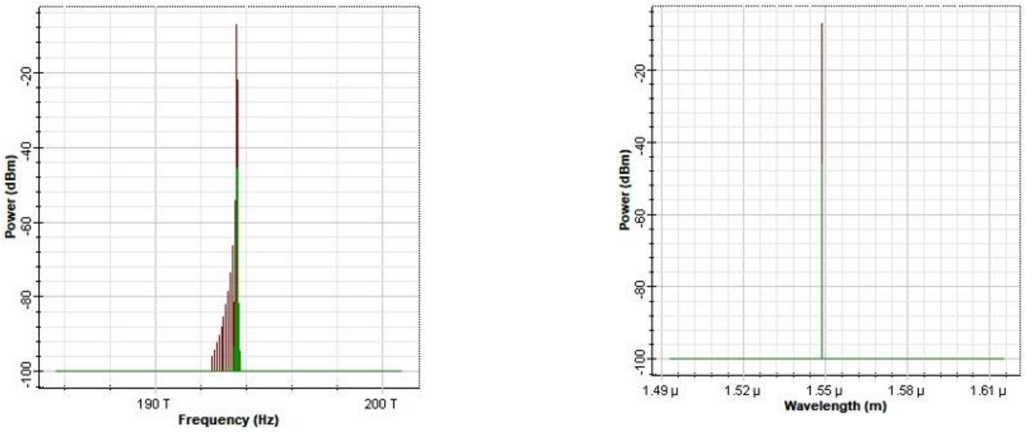
Fig. 2. The measurement of Signal-to-Noise Ratio (SNR) from 12 channels of Dense Wavelength Division Multiplexing (DWDM) at the Erbium-Doped Fiber Amplifier (EDFA) output.

noise suppression. Thus, the performance of the system can be enhanced because the noise modulation is suppressed by setting a narrow FBG and electrical signal bandwidth as the output of the Gaussian filter is also minimized.

III. RESULTS AND DISCUSSION

Figure 2 shows the results of SNR measurements. The EDFA-Tx is set at an output of 5 dBm. It amplifies the signal of 12 channels from the Mux at the level of 28 dBm. As shown in Fig. 2(a), all channels are almost flat, and there are no gain fluctuations. In Fig. 2(b), the EDFA-Rx is set at 5 dBm, and the node spacing is 500 m. The SNR result shows an average of 28.7 dB. In Fig. 2(c), the EDFA Rx is set at 10 dBm, and the node spacing is 1,000 m. The output of the average SNR is 23.9 dB. In Fig. 2(d), the EDFA-Tx is set at 19 dBm. The EDFA-Rx is 5 dBm, and the node spacing is 1,500 m. The output of the average SNR is 23.5 dB. In Fig. 2(e), the EDFA-Tx is set at 25 dBm, and the EDFA-Rx is set at 10 dBm. Meanwhile, the node spacing is 2,000 m. The output of the average SNR is 22.1 dB. In Fig. 2(f), the EDFA-Tx is set at 30 dBm, and the EDFA-Rx is set at 15 dBm. The node spacing is 2,500 m. The output of the average SNR goes lower to 18 dB. In all the scenarios with nodes spaced from 500 m to 2,500 m, the EDFA-Rx still produces flattened gain for all channels. This EDFA-Rx gaining profile spectrum allows the distributed signal to be forwarded to the Li-Fi access networks without significant variations between each channel.

Figure 2 shows that the node spacing effect reduces the power of the signal. The node spacing is the path length of optical propagation in the open air of the city that may attenuate the optical signal from the telescope Tx to the telescope Rx. In the simulation, the attenuation factor is set to a uniform 10 dB/km by assuming that the Rytov factor is lower. Thus, scintillation is also at a minimum because the height of optical propagation in the open air is lower than 500 m or near ground level. However, even though the scintillation is lower, noise modulation still induces



(a) The signal power of channel-3 as the output of the FBG shows noise modulation around the center wavelength.

(b) The results of filtering by an FBG and a Gaussian filter for channel-3.

Fig. 3. The noise modulation filtering via a Fiber Bragg Grating (FBG) and a Gaussian filter. The output signal from the FBG with a Signal-to-Noise Ratio (SNR) of 29.15 dB enhanced with a Gaussian filter produces an SNR of 29.62 dB.

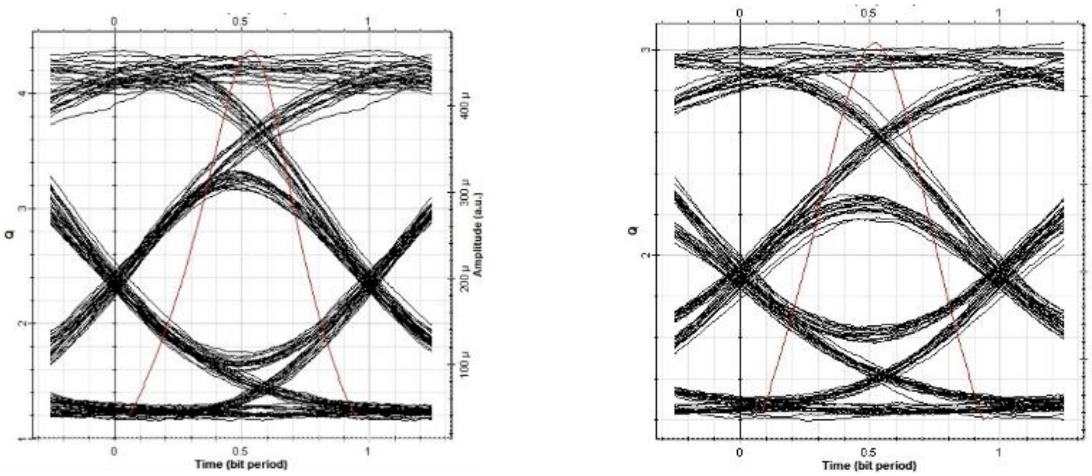
optical propagation. Noise modulation is induced by the phenomena of light scattering by particles, such as aerosols or dust, in the open-air environment of a city.

Next, a filtering technique is applied to minimize noise modulation. The FBG has the main role of only forwarding the selected channel from the De-Mux through the Li-Fi access network. Instead of channel selection, it must also minimize noise modulation that is amplified during reception by the EDFA-Rx, as well as any noise in the output. Thus, the selected channel can be received by the PD of the Li-Fi access network with less noise. The output signal of the FBG is filtered spatially to ensure that noise is optimally suppressed at the center wavelength or channel to minimize noise modulation. The spatial filter uses a Gaussian filter that implements the bandpass technique at the bandwidth of 10 Gbps. As shown in Fig. 3(a), the FBG output selects only specified channels. However, noise is still modulated as it has been amplified by the EDFA-Rx. In Fig. 3(b), the output of the FBG is filtered by a Gaussian filter. The output spectrum shows a signal with minimum noise around the center wavelength or channel. The Gaussian filter suppresses noise to improve the signal quality to 0.47 dB. Through the filtering technique, 12 channels will go to the Li-Fi access network with the minimum noise modulation. Thus, the output of the Gaussian filter will be received by the PD of the Li-Fi network and forwarded to the users across the last mile at a rate of 10 Gbps for each access point in the distributed network.

After the optical signal for each channel is filtered via an FBG and a Gaussian filter, the PD receives the optical signal and converts it into an electrical signal. The performance of the electrical signal resulting from the PD can be seen in the eye diagrams in Fig. 4(a) and 4(b). Figure 4(a) shows the result of the electrical signal that is received by the PD without implementing a Gaussian filter previously. The electrical signal is a little bit noisy, and the transition of the signal is almost raw as well. The electrical signals improve after implementing the Gaussian filter, as shown in Fig. 4(b). There is a smooth transition between the sending and receiving units. It means the Gaussian filter optically suppresses the noise that is modulated around the center of the wavelength to minimize the signal fluctuation. Thus, the PD produces an electrical current with minimum fluctuation as well.

Figure 5 shows the BER performance for 12 channels in the scenario of nodes spaced at 500 m, 1,000 m, 1,500 m, 2,000 m, and 2,500 m. It can be seen that the node spacing distance has a serious impact on BER performance. The best BER performance is achieved at the lowest spacing, and the longest spacing produces the worst quality. Also, the BER fluctuation between each channel in the same node spacing distance does not exhibit large variations. On average, the BER variations at the same node spacing distance are on the order of 10^{-1}. The 12 channels produce almost linear BER performance for the same node spacing distance.

Based on Fig. 5, it can also be inferred that for a reliable connection to support the Li-Fi access network, the node spacing distance should be as short as possible to minimize noise modulation. Reliable performance is found with a connection range between 500 m and 2,000 m. Beyond 2,000 m, the noise modulation tends to degrade the signal performance, producing



(a) The eye diagram from the output of the Photodetector (PD) without implementing a Gaussian filter previously.

(b) The eye diagram from the implementation of Gaussian filter before the Photodetector (PD).

Fig. 4. The Eye diagram measurement indicating the quality of the electrical signal from the Photodetector (PD) output of the Li-Fi access network.

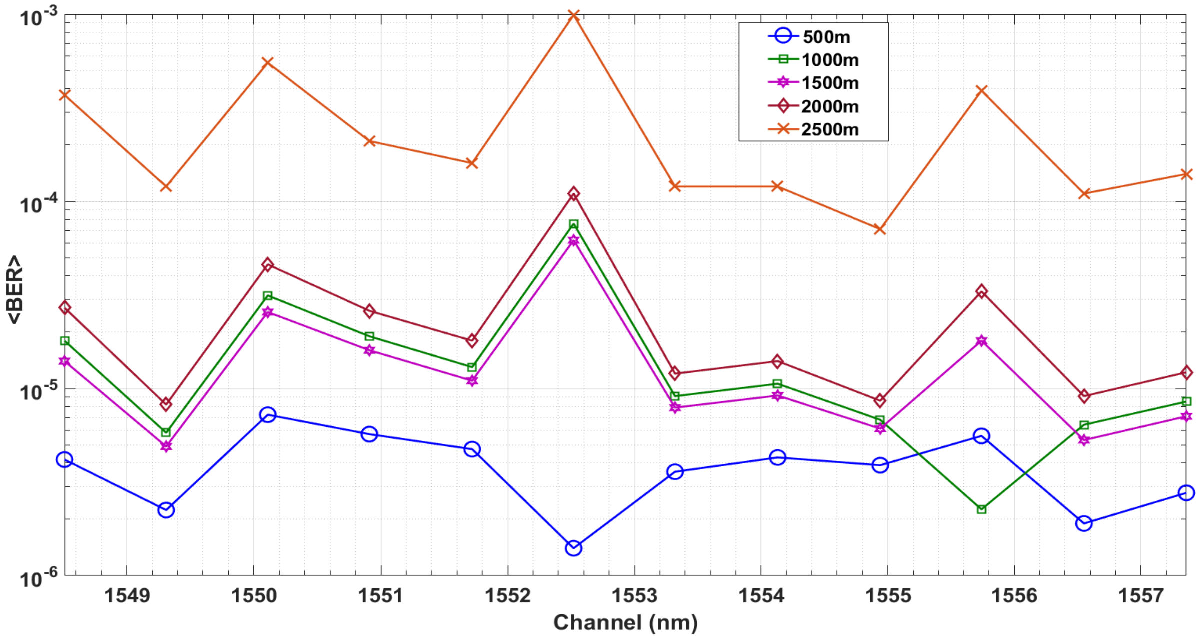


Fig. 5. Bit-Error-Rate (BER) performance measurements for 12 channels where the spacing nodes are 500 m, 1,000 m, 1,500 m, 2,000 m, and 2,500 m.

the worst BER performance on the order of 10^{-3}. All DWDM channels have also shown linear BER performance, which means great fluctuation between each channel does not exist in the simulation. This condition provides a last-mile data connection between the backbone FSO and the Li-Fi hub in a city with excellent signal characteristics and performance. Thus, FSO can deliver one or more high-data-rate channels into the Li-Fi access network. The Li-Fi access network can broadcast data on a scale of 40 Gbps [37–40].

To date, only an optical fiber communications platform can support this requirement. However, by using FSO as the backbone, this requirement can be supported optimally with the implementation of channel allocation to support the data transmission rate. It means the implementation of the DWDM system on an FSO backbone can also support flexible distribution and allocation for the data transmission rate. The bandwidth allocation requirement in the Li-Fi access network can be regulated via channel assignment or selection. The significant result based on the implementation of DWDM on FSO that is capable of delivering 120 Gbps into Li-Fi access networks is the performance of BER is achieved at the order of 10^{-6}–10^{-3} for a node spacing distance ranging from 500 m to 2,500 m. That result is achieved by implementing an EDFA on the Tx and Rx, where the output of the receiving PD is filtered by an FBG and a Gaussian filter. Thus, integrated Li-Fi over FSO can be implemented in a smart city to provide high bitrate transmission and a high-reliability access network.

IV. CONCLUSION

The use of FSO as the backbone network for the distributed Li-Fi in a smart city has been simulated. The C-band of the DWDM is used as the channels, where each carries 10 Gbps. The total data transmission bitrate is 120 Gbps, which is distributed to support the Li-Fi network. The simulation results reveal that node spacing is a critical element of backbone design when using FSO. Nodes must be spaced in a range of 500 m to 2,000 m to ensure a reliable connection. The main factors that can enhance the performance of FSO when used to support a Li-Fi access network are an optical amplifier (EDFA-Tx and -Rx), a filtering method from channel selection to spatial technique to minimize noise modulation, and the node spacing distance. Thus, FSO can be implemented as the backbone access network for Li-Fi to cover a smart city over a distance order of 101 km.

FSO has the potential to be implemented as the backbone access for distributed Li-Fi networks. It is very capable of supporting high bitrate transmission on the order of 102 Gbps with a high speed as well. Li-Fi technology demands an infrastructure network that can deliver data transmission on the order minimum of 10 Gbps. Also, FSO is flexible and can be configured following the topology of a city, even when dominated by high-rise buildings. The major problem of FSO, which is scintillation caused by atmospheric turbulence, is avoided by implementing the FSO in the air just above ground level. Thus, FSO can support the delivery of an access network for distributed Li-Fi in a smart city. The implementation of DWDM in a backbone FSO system also provides flexibility when allocating bandwidth.

As a connection hub in a smart city, Li-Fi is designed to connect IoT items that need to be monitored, processed, and controlled. Thus, the Li-Fi access network needs a high data transmission rate to ensure a reliable connection. The DWDM channels can be selected and allocated to support the Li-Fi access network requirements. Each channel can be provided in an order of 10 Gbps. The DWDM channels provide bandwidth across a range of 10 Gbps to 40 Gbps. However, this is not a limiting case. The remaining DWDM system can provide higher rates depending on the capacity of the Li-Fi access network to broadcast multiple last-mile connections to users or unlimited things in the IoT configuration.

The limitation of the simulated FSO lies in the type of modulation, which is based on Return to Zero (RZ) or NRZ signals. Meanwhile, signal modulation techniques, such as Pulse Position Modulation (PPM) and Pulse Shift Keying Modulation (PSK), have advanced. Thus, for further FSO simulation, an advanced type of signal modulation can be implemented to seek the best performance in terms of BER. Another challenge for integrating Li-Fi over FSO is harvesting solar energy as the source of electricity and providing road lighting at night. These challenges must address the limitation of Li-Fi in the LED Tx components. To date, these components cannot simultaneously emit visible light and modulate high bitrate transmissions.

Finally, a smart city concept that needs a reliable access network infrastructure can be supported by integrating FSO as the backbone and a Li-Fi network as the hub to reach all users. FSO and Li-Fi are a perfect combination to ensure that the physical connection infrastructure is a green technology that supports a smart city. It is different from a physical infrastructure that is based on microwave broadcasting, where electrical energy consumption is a great issue. FSO and Li-Fi are the physical connection platforms that are competitive in terms of electrical energy consumption. This combination or integration can support the implementation of green technology in a smart city.

ACKNOWLEDGEMENT

The researchers acknowledge funding support from Kementerian Pendidikan dan Kebudayaan Republik Indonesia, Hibah Penelitian Kompetitif at the scheme of Penelitian Terapan – Jalur Hilirisasi Tahun 2023 Contract Number of 179/E5/PG.02.00.PL/2023, 1425/LL3/AL.04/2023, 100/A/LPPM-UNAS/VII/2023. The researchers also acknowledge the support from LPPM of Universitas Nasional for outstanding help and guidance in conducting research in the Laboratory of Optical Communications and Network and LPPM Universitas Siber Asia. The researchers also thank students (Agung Riyadi, Simon, and Handa) who helped the experiment as the plan of research. Finally, the researchers thank all anonymous reviewers who helped to improve the manuscript throughout the publication process.

AUTHOR CONTRIBUTION

Writing—original draft, U. D., and N. D. N.; Methodology, U. D., and N. D. N.; Formal analysis, U. D., and P. S. P.; Analysis result review, U. D., N. D. N., M. Z., and P. S. P. All authors have read and agreed to the published version of the manuscript.

REFERENCES

[1] H. H. Khan, M. N. Malik, R. Zafar, F. A. Goni, A. G. Chofreh, J. J. Klemeš, and Y. Alotaibi, "Challenges for sustainable smart city development: A conceptual framework," *Sustainable Development*, vol. 28, no. 5, pp. 1507–1518, 2020.

[2] Y. Lim, J. Edelenbos, and A. Gianoli, "Identifying the results of smart city development: Findings from systematic literature review," *Cities*, vol. 95, 2019.

[3] S. P. Caird and S. H. Hallett, "Towards evaluation design for smart city development," *Journal of Urban Design*, vol. 24, no. 2, pp. 188–209, 2019.

[4] T. R. Bhattacharya, A. Bhattacharya, B. Mclellan, and T. Tezuka, "Sustainable smart city development framework for developing countries," *Urban Research & Practice*, vol. 13, no. 2, pp. 180–212, 2020.

[5] M. Peris-Ortiz, D. R. Bennett, and D. P.-B. Yábar, "Sustainable smart cities," in *Innovation, Technology, and Knowledge Management*. Springer International Publishing Switzerland, 2017.

[6] G. Yadav, S. K. Mangla, S. Luthra, and D. P. Rai, "Developing a sustainable smart city framework for developing economies: An Indian context," *Sustainable Cities and Society*, vol. 47, 2019.

[7] T. A. Oliveira, M. Oliver, and H. Ramalhinho, "Challenges for connecting citizens and smart cities: ICT, e-governance and blockchain," *Sustainability*, vol. 12, no. 7, pp. 1–21, 2020.

[8] B. S. Sergi, A. Berezin, N. Gorodnova, and I. Andronova, "Smart cities and economic growth in Russia," in *Modeling economic growth in contemporary Russia*. Emerald Publishing Limited, 2019, pp. 249–272.

[9] C. C. Okafor, C. O. Aigbavboa, O. I. Akinradewo, and W. D. Thwala, "The future of smart city: A review of the impending smart city technologies in the world," in *IOP Conference Series: Materials Science and Engineering*, vol. 1107, no. 1. IOP Publishing, 2021, pp. 1–7.

[10] W. Shuai, P. Maillé, and A. Pelov, "Charging electric vehicles in the smart city: A survey of economy-driven approaches," *IEEE Transactions on Intelligent Transportation Systems*, vol. 17, no. 8, pp. 2089–2106, 2016.

[11] P. G. V. Naranjo, Z. Pooranian, M. Shojafar, M. Conti, and R. Buyya, "FOCAN: A Fog-supported smart city network architecture for management of applications in the Internet of Everything environments," *Journal of Parallel and Distributed Computing*, vol. 132, pp. 274–283, 2019.

[12] L. Guevara and F. Auat Cheein, "The role of 5G technologies: Challenges in smart cities and intelligent transportation systems," *Sustainability*, vol. 12, no. 16, pp. 1–15, 2020.

[13] F. Cirillo, D. Gómez, L. Diez, I. E. Maestro, T. B. J. Gilbert, and R. Akhavan, "Smart city IoT services creation through large-scale collaboration," *IEEE Internet of Things Journal*, vol. 7, no. 6, pp. 5267–5275, 2020.

[14] F. Al-Turjman, H. Zahmatkesh, and R. Shahroze, "An overview of security and privacy in smart cities' IoT communications," *Transactions on Emerging Telecommunications Technologies*, vol. 33, no. 3, pp. 1–19, 2022.

[15] I. Dolińska, M. Jakubowski, and A. Masiukiewicz, "Interference comparison in Wi-Fi 2.4 Ghz and 5 Ghz bands," in *2017 International Conference on Information and Digital Technologies (IDT)*. Zilina, Slovakia: IEEE, July 5–7, 2017, pp. 106–112.

[16] A. S. Haron, Z. Mansor, I. Ahmad, and S. M. M. Maharum, "The performance of 2.4 GHz and 5GHz Wi-Fi router placement for signal strength optimization using Altair WinProp," in *2021 IEEE 7th International Conference on Smart Instrumentation, Measurement and Applications (ICSIMA)*. Bandung, Indonesia: IEEE, Aug. 23–25, 2021, pp. 25–29.

[17] R. Badeel, S. K. Subramaniam, Z. M. Hanapi, and A. Muhammed, "A review on LiFi network research: Open issues, applications and future directions," *Applied Sciences*, vol. 11, no. 23, pp. 1–35, 2021.

[18] X. Wu, M. D. Soltani, L. Zhou, M. Safari, and H. Haas, "Hybrid LiFi and WiFi networks: A survey," *IEEE Communications Surveys & Tutorials*, vol. 23, no. 2, pp. 1398–1420, 2021.

[19] M. Asif, T. A. Khan, N. Taleb, R. A. Said, S. Y. Siddiqui, and G. Batool, "A proposed architecture for traffic monitoring & control system via LiFi technology in smart homes," in *2022*

International Conference on Business Analytics for Technology and Security (ICBATS). Dubai, United Arab Emirates: IEEE, Feb. 16–17, 2022, pp. 1–3.

[20] S. M. Kouhini, C. Kottke, Z. Ma, R. Freund, V. Jungnickel, M. Müller, D. Behnke, M. M. Vazquez, and J. P. M. G. Linnartz, "LiFi positioning for Industry 4.0," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 27, no. 6, pp. 1–15, 2021.

[21] S. A. Al-Gailani, M. F. M. Salleh, A. A. Salem, R. Q. Shaddad, U. U. Sheikh, N. A. Algeelani, and T. A. Almohamad, "A survey of Free Space Optics (FSO) communication systems, links, and networks," *IEEE Access*, vol. 9, pp. 7353–7373, 2020.

[22] S. Shah, M. Siddharth, N. Vishwakarma, R. Swaminathan, and A. S. Madhukumar, "Adaptive-combining-based hybrid FSO/RF satellite communication with and without HAPS," *IEEE Access*, vol. 9, pp. 81 492–81 511, 2021.

[23] A. A. B. Raj, P. Krishnan, U. Darusalam, G. Kaddoum, Z. Ghassemlooy, M. M. Abadi, A. K. Majumdar, and M. Ijaz, "A review–unguided optical communications: Developments, technology evolution, and challenges," *Electronics*, vol. 12, no. 8, pp. 1–97, 2023.

[24] U. Darusalam, F. Y. Zulkifli, P. S. Priambodo, and E. T. Rahardjo, "Hybrid optical communications for supporting the Palapa Ring network," *Bulletin of Electrical Engineering and Informatics*, vol. 9, no. 3, pp. 1055–1066, 2020.

[25] O. Faruq, K. R. S. Rahman, N. Jahan, S. Rokoni, and M. Rabeya, "Li-Fi technology-based long-range FSO data transmit system evaluation," *Sustainable Engineering and Innovation*, vol. 5, no. 1, pp. 85–98, 2023.

[26] S. H. Alnajjar and B. K. ALfaris, "OCDMA performance on FSO turbulent weather channel on Li-Fi systems," *Al-Iraqia Journal for Scientific Engineering Research*, vol. 1, no. 2, pp. 1–8, 2022.

[27] M. J. Mohsin and I. A. Murdas, "Performance analysis of an outdoor Li-Fi system-based AO-OFDM architecture under different FSO turbulence and weather conditions," *Optik*, vol. 273, 2023.

[28] S. Liverman, Q. Wang, Y. J. Chu, A. Borah, S. Wang, A. Natarajan, A. X. Wang, and T. Nguyen, "WiFO: A hybrid communication network based on integrated free-space optical and WiFi femtocells," *Computer Communications*, vol. 132, pp. 74–83, 2018.

[29] A. Jahid, M. H. Alsharif, and T. J. Hall, "A contemporary survey on free space optical communication: Potentials, technical challenges, recent advances and research direction," *Journal of Network and Computer Applications*, vol. 200, 2022.

[30] S. Alfattani, "Review of LiFi technology and its future applications," *Journal of Optical Communications*, vol. 42, no. 1, pp. 121–132, 2021.

[31] U. Darusalam, A. B. Raj, F. Y. Zulkifli, P. S. Priambodo, and E. T. Rahardjo, "Performance of free-space optical communication systems using optical amplifiers under amplify-forward and amplify-received configurations," *Makara Journal of Technology*, vol. 24, no. 3, pp. 117–124, 2020.

[32] U. Darusalam, F. Y. Zulkifli, P. S. Priambodo, and E. T. Rahardjo, "Full-duplex of optical relaying network in FSO communications to provide broadband Internet connection in rural area," in *2019 IEEE R10 Humanitarian Technology Conference (R10-HTC)(47129)*. Depok, Indonesia: IEEE, Nov. 12–14, 2019, pp. 71–75.

[33] P. Ariyanto, A. Iskandar, and U. Darusalam, "Rancang bangun Internet of Things (IoT) pengaturan kelembaban tanah untuk tanaman berbasis mikrokontroler," *Jurnal JTIK (Jurnal Teknologi Informasi dan Komunikasi)*, vol. 5, no. 2, pp. 112–118, 2021.

[34] U. Darusalam, A. B. Raj, F. Y. Zulkifli, P. S. Priambodo, and E. T. Rahardjo, "The relaying network in free-space optical communications using optical amplifiers in cascaded configuration," *Makara Journal of Technology*, vol. 27, no. 2, pp. 58–67, 2023.

[35] U. Darusalam, P. S. Priambodo, and E. T. Rahardjo, "Noise filtering in the output of photodetector to enhance the performance of optical relaying networks on FSO communications," in *2021 17th International Conference on Quality in Research (QIR): International Symposium on Electrical and Computer Engineering*. Depok, Indonesia: IEEE, Oct. 13–15, 2021, pp. 98–103.

[36] ——, "Optical spatial filter to suppress beam wander and spatial noise induced by atmospheric turbulence in free-space optical communications," *Advances in Optical Technologies*, vol. 2015, pp. 1–6, 2015.

[37] Y. S. Hussein and A. C. Annan, "Li-Fi technology: High data transmission securely," in *Journal of Physics: Conference Series*, vol. 1228, no. 1. IOP Publishing, 2019, pp. 1–10.

---

[38] W. S. Tsai, H. H. Lu, C. Y. Li, T. C. Lu, C. H. Liao, C. A. Chu, and P. C. Peng, “A 50 m/40 Gbps 680-nm VCSEL-based FSO communication,” in *2016 IEEE Photonics Conference (IPC)*. Waikoloa, USA: IEEE, Oct. 2–6, 2016, pp. 39–40.

[39] C. Y. Li, H. H. Lu, T. C. Lu, W. S. Tsai, B. R. Chen, C. A. Chu, C. J. Wu, and C. H. Liao, “A 100m/40Gbps 680-nm VCSEL-based LiFi transmission system,” in *2016 Conference on Lasers and Electro-Optics (CLEO)*. San Jose, USA: IEEE, June 5–10, 2016, pp. 1–2.

[40] M. Sahu, K. V. Kiran, and S. K. Das, “FSO link performance analysis with different modulation techniques under atmospheric turbulence,” in *2018 Second International Conference on Electronics, Communication and Aerospace Technology (ICECA)*. Coimbatore, India: IEEE, March 29–31, 2018, pp. 619–623.