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Hybrid Radio over Fiber with Radio over Free Space Optic for 5G Fronthaul Network Implementation in Urban Areas

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Abstract—**Optical fiber can meet the demand for fronthaul on 5G networks that offer high bandwidth, large capacity, high data rate, and free from electromagnetic interference. However, deploying infrastructure faces issues like permits and high costs. Hybrid radio over fiber (RoF) technology with radio over free space optic (RoFSO) can be a solution in urban areas, where the installation requires high costs. This research investigates a hybrid RoF-RoFSO scheme at a frequency of mmWave 26 GHz by considering atmospheric attenuation values arising from meteorological effects, such as rain, smog, and haze, using Optisystem. This research considers QPSK, 16-QAM, and 64-QAM modulation schemes, distance variations on the FSO, and the meteorological data from the Indonesian Meteorology, Climatology and Geophysics Agency (BMKG) from March 2022 to May 2022. The results show that attenuation due to high rainfall is the main cause of signal quality degradation and limits the transmission distance on the FSO link. The maximum distance is 600 m using the QPSK and 16-QAM modulation schemes, while for the 64-QAM modulation scheme, the maximum transmission distance is 500 m. Meanwhile, damping values caused by dusty and haze conditions can reach distances of up to 1000 m for the three modulation schemes.**

Keywords: ***optical fiber, radio over fiber (RoF), fronthaul, radio over fiber space optic (RoFSO), atmospheric attenuation***

I. Introduction

The Internet is one of the communication services that is continuously developed and improved. The performance of high-speed and low-latency internet technology makes it possible to carry out various activities anywhere and anytime. Of the many features, internet users use video streaming applications most widely. According to a study conducted by Sandvine, 70% of internet traffic today comes from video streaming applications such as Netflix, YouTube, Twitch, and so on [1]. In addition, Cisco estimates that traffic from video streaming services will account for 82% of total global Internet traffic by 2022 [2].

As the number of video streaming users increases, application service providers need to improve the quality of their user experience (QoE) by increasing the resolution of streaming video. However, providing high resolution requires higher network speeds. 4G technology can only connect users with download speeds of up to 10 Mbps user experience. Not all users can feel download speeds up to that amount, so the existing network speed is mostly impossible to meet internet users' needs in the future. This condition certainly encourages researchers to develop faster and more efficient communication technology, especially cellular technology. Cellular technology has entered the fifth generation, or 5G, expected to meet user needs for high bandwidth, with speeds higher than 4G, which is 20 Gbps or around 100 Mbps user experience. This high speed is necessary to meet the data transmission needs of VOD applications and provide a much better user experience.

According to the 5G Alliance for Connected Industries and Automation (5G-ACIA) and 3GPP, 5G technology has three types of services: enhanced mobile broadband (eMBB), ultra-reliable and low-latency communications (uRLLC), and massive machine-type communications (mMTC) [3]. The difference in transmission characteristics in each service is the main obstacle to accessing the full potential of 5G technology. Existing network infrastructure cannot provide the flexibility, scalability and level of automation expected from 5G technology. Thus, network operators must redefine their operating architecture and network services to meet existing service requirements.

Network slicing is a form of virtualization that allows various services with different requirements to run on the same physical infrastructure while guaranteeing the requirements of each service on 5G. This method allows 5G networks to provide high-speed connections with high reliability and low latency, making 5G a network for various use cases [4]. Using network slicing on C-RAN

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can make 5G networks more flexible, improving network performance and efficiency and enabling better frequency utilization [5]-[6]. In the C-RAN architecture, the backhaul network connects the Central Station (CS) with the core network, while the fronthaul network connects the CS to the remote radio unit (RRU) located at the base station (BS).

Telecommunications service providers use technology that combines fiber optics and radio waves or radio over fiber (RoF) as a fronthaul network. Most of the use of RoF in 5G is based on digital RoF (D-RoF), where analog radio signals are first converted into digital form in RRU before transmitting through optical fiber [7]. Changes in analog-to-digital signals on RRUs cause low spectral efficiency and increase network delay. On the other hand, there is analog RoF (A-RoF) as opposed to D-RoF, where A-RoF retains the shape of analog radio signals in the optical domain when transmitted over optical fiber [8]. However, applying RoF technology in general through A-RoF and D-RoF has obstacles in the installation process. Diverse geographical conditions and high costs are the main obstacles to deploying fiber optic infrastructure in rural areas. In urban areas, deploying fiber optic infrastructure requires high costs and a long time, so obtaining permits from the local government is difficult. One alternative technology to overcome these obstacles is to utilize radio waves through free space optic (FSO) technology on fronthaul networks.

FSO technology is a communication technology that utilizes free space as a signal transmission medium. In principle, FSO technology is closely related to fiber optic communication. FSO technology can provide high capacity with immunity to radio wave interference like optical fiber [9]. The application of FSO as a transmission channel for radio waves is a modified technology of RoF known as Radio over Free Space Optics (RoFSO). The RoFSO concept offers high flexibility like wireless communication and speeds comparable to fiber optic communication [10]-[11]. However, in RoFSO technology, the transmission quality is strongly influenced by atmospheric conditions [12]. Meteorological effects in the atmosphere, such as haze, rain, dust, and snow, can cause partial or complete loss of information due to absorption and scattering and limit network performance and transmission distances [13]–[15]. Therefore, hybrid RoF-RoFSO technology can be a potential solution on fronthaul networks to improve network reliability and provide high-speed connectivity to its users.

Numerous studies have been conducted to analyze the effects of atmospheric conditions on the performance of FSO systems. Haze is a considerable factor causing attenuation in the atmosphere because the size of particles is comparable to the optical transmission wavelength [16]. Studies in [17] show that the effect of fog on the performance of FSO systems has been carried out in South Africa. This study shows that the maximum distance the FSO can reach in Johannesburg and Cape Town in foggy conditions is 350 meters. While in Mafikeng, the maximum distance the FSO can reach is 550 meters. Another study was conducted in Nigeria, where the performance of the FSO system was evaluated under fog and rainy conditions [18]. The results showed foggy conditions gave a higher attenuation value than rainy conditions. The maximum distance that can be achieved is 300 meters in foggy conditions and 2000 meters in rainy conditions.

Studies have been conducted using 16-QAM and 64-QAM modulation schemes [19]. Based on the analysis, the 16-QAM and 64-QAM modulation schemes can cover 1 km of the optical fiber link and 20 meters of the FSO link. A similar study was conducted in [20], using 4-QAM, 16-QAM, and 64-QAM modulation schemes. The result shows that the maximum error vector magnitude (EVM) limit can be fulfilled up to 5 km using the optical fiber link and 500 meters using the FSO link with EVM 15%, 11.6%, and 7.7% for the 4-QAM, 16-QAM, and 64-QAM modulation schemes, respectively.

In this study, a hybrid RoF-RoFSO system will be designed as a fronthaul network to support the implementation of 5G networks in Urban Areas. In this study, a hybrid RoF-RoFSO system was designed to apply 5G fronthaul in urban areas at a frequency of 26 GHz with QPSK, 16-QAM, and 64-QAM modulation schemes. It analyzed the effect of rain, haze, and dust in the atmosphere on the performance of the RoF-RoFSO hybrid system, which was characterized based on bit error rate (BER) and EVM values.

II. RADIO OVER FREE SPACE OPTIC

Radio over Free Space Optic (RoFSO) is a modified technology of RoF technology, where free space or atmosphere is used as a transmission medium in this technology. RoFSO is a promising technology for the future because it can solve congestion in access networks due to the high bandwidth needed. Using RoFSO in communication can also overcome obstacles in deploying optical fiber due to diverse geographical conditions. In addition, RoFSO can be a solution for rural areas where fiber optic infrastructure has not been built due to high costs or low population. Figure 1 shows the schematic of the RoF-RoFSO hybrid system as a fronthaul network in an urban area.

On the other hand, the weakness of RoFSO technology lies in its transmission medium, the atmosphere. The signal will weaken in optical fibers as the transmission

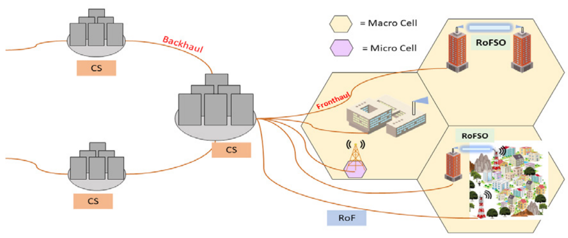

Figure 1. Schematic of the RoF-RoFSO hybrid system as a fronthaul network in urban areas [21]- [22]

distance increases due to the fiber's attenuation. In RoFSO, atmospheric attenuation is unpredictable and can cause attenuation ranging from a few dB to hundreds of dB per kilometer [23]. The damping effect on the atmosphere occurs due to haze, rain, smog and dust, and snow [13]. Studies have shown that haze is the highest factor causing attenuation in the atmosphere due to the size of haze particles being proportional to optical transmission wavelengths and close to infrared waves [16]. However, fog and snow are not factors for tropical regions such as Indonesia. For Indonesia, high rainfall, dust and haze are the main factors that cause high attenuation in the atmosphere.

Rain attenuation is one of the causes of the scattering effect on the atmosphere that needs to be considered after fog because fog does not occur in the tropics. Atmospheric scattering is divided into Rayleigh, noodle, and nonselective. Nonselective scattering occurs when the particle size is much larger than the wavelength. Nonselective scattering is independent of wavelength and can occur due to precipitation [24]. The estimated attenuation value due to rainfall can be calculated by Equation 1 [25]. R is precipitation in mm, k and α are power parameters that depend on frequency, raindrop size, temperature, and polarization.

$$\gamma_{rain} = kR^{\alpha} \quad (1)$$

In calculating rain attenuation, it can be assumed that the raindrops are spherical, making k and α not depend on polarization. The value of k can be calculated using the Marshal and Carbonneau models. Based on ITU recommendations, the Carbonneau model can be used to calculate rain attenuation because the effect of the Carbonneau model is greater than that of the Marshal model [26]-[27]. The Carbonneau model uses physical methods based on measurement data. For the Carbonneau model, the k and α values are 1.076 and 0.67, respectively, so the rain attenuation values can be calculated by Equation 2.

$$\gamma_{rain} = 1.076R^{0.67} \quad (2)$$

Smog occurs when the atmosphere contains dust particles and pollutants, while haze occurs due to water droplets. Like fog, smog particles can stay longer in the atmosphere, which can cause performance degradation in RoFSO. A damping model can be used to find attenuation due to smog, as in Equation 3 [25].

$$\gamma_{haze} = \frac{3,91}{V}\left(\frac{\lambda}{550}\right)^{-p} \quad (3)$$

The value of V is the visibility in kilometers (km), λ is the wavelength used, and p is the particle size coefficient. Based on the Kruse model [28], the given p-value is

$$P = \begin{cases} 1.6 & V > 50\text{km} \\ 1.3 & 6\text{km} < V < 50\text{km} \\ 0.58V^{-1/3} & V < 6\text{km} \end{cases}$$

However, the Kruse model cannot model p for distances less than 1 km. Another formula known as the Kim model [29] was formulated to calculate damping at visibility below 1 km, where the p-parameter value has been modified as follows.

$$P = \begin{cases} 1.6 & V > 50\text{km} \\ 1.3 & 6\text{km} < V < 50\text{km} \\ 0.16V + 0.34 & 1\text{km} < V < 6\text{km} \\ V - 0.5 & 0.5\text{km} < V < 1\text{km} \\ 0 & V < 0.5\text{km} \end{cases}$$

Table 1. Optical sender specification [30]

Specifications	Value
Bit Rate	10 Gbps
Modulation Type	QPSK, 16-QAM, dan 64-QAM
Radio Frequency	26 GHz
Wavelength	1550 nm(C-Band)
Modulator optics	Mach Zehnder Modulator
Laser Power	15 dBm

III. Design and Simulation

Figure 2 shows the schematic circuit of the RoF-RoFSO simulation. Table I shows the specification of transmitter components considered in this study. In this simulation, the radio frequency used is 26 GHz, a candidate for Indonesia's 5G mmWave frequency. The BER Test component generates binary signals with a bit rate of 10 Gbps and will be fed into the QAM/PSK Sequence Generator to generate M-ary symbols. Next, the signal is forwarded to the OFDM Modulator. OFDM modulators are used to modulate the digital signal into several orthogonal subcarriers, which are then filtered using a low-pass cosine roll-off filter. Then, the modulated OFDM signal will be used to modulate the 26 GHz RF carrier signal generated using the Quadrature Modulator and produce a QAM or QPSK modulated carrier signal. CW Laser is an optical source to modulate the RF frequency of 26 GHz using MZM and will produce a carrier optical signal. Furthermore, the QAM/QPSK modulated OFDM signal will be modulated with a sound optical device.

The modulated optical signal will be transmitted through two different transmission channels. First, the optical signal will go through a transmission channel in the form of optical fiber, where the type of fiber used is a single-mode optical fiber. Single-mode optical fibers were used in this study because of their characteristics with minimal pulse widening so that they are more resistant to dispersion effects leading to Intersymbol Interference (ISI). The resistance of single-mode optical fibers to ISI makes the optical signals transmitted by these optical fibers carry high bandwidth in the gigahertz range. The type of cable used in this study is Corning SMF-28 Ultra Optical Fiber, per the recommendations of ITU-T-REC-G.652-201611. The optical fiber used in this study works at a frequency of 1550 nm with a fiber attenuation value of 0.17 dB/km. Further, optical fiber specifications can be seen in Table 2 [31]-[32].

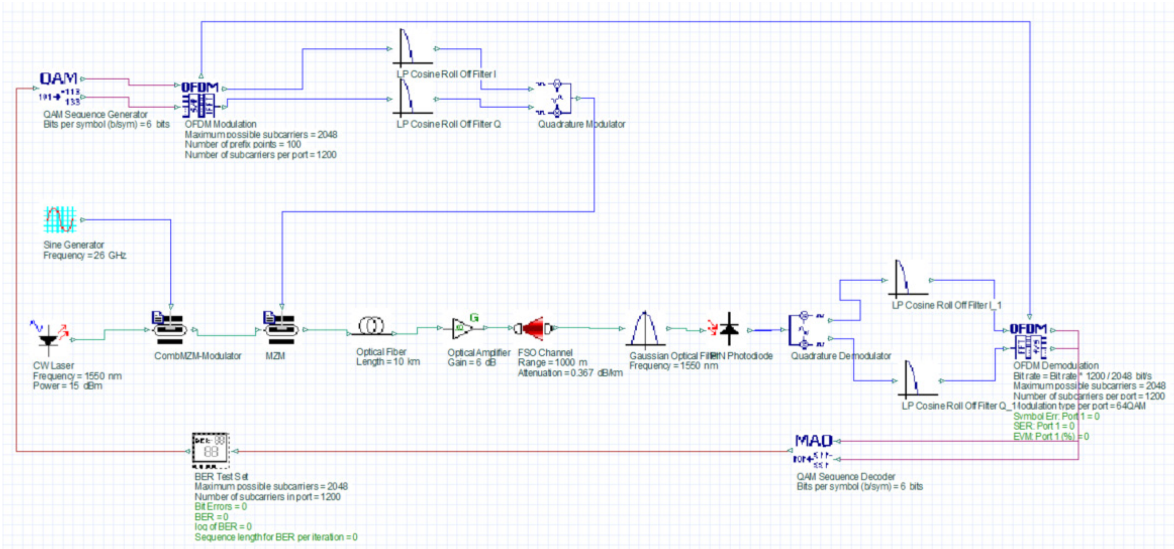

Figure 2. Schematic circuit simulation hybrid radio over fiber (RoF) – radio over free space optic (RoFSO)

After the optical signal is transmitted through the optical fiber, then the optical signal will be transmitted through the free space, which is the atmosphere. When optical signals are transmitted through the atmosphere, they can be attenuated by meteorological effects such as rain, haze, dust, and snow. This meteorological effect makes atmospheric attenuation values arbitrary and is the main cause of signal degradation in FSO. Therefore, it is necessary to determine atmospheric attenuation values under various conditions. By calculating the rain attenuation using Equation 2, the damping values obtained for rainy conditions in the period March 2022 – May 2022 were 0.367 dB/km, 3.68 dB/km, 11.53 dB/km, 0.58 dB/km, 5.6 dB/km, 16.35 dB/km, 4.62 dB/km, and 11.7 dB/km.

Meanwhile, by using Equation 3, the damping values for haze and dust conditions are 0.986 dB/km, 0.143 dB/km, 0.101 dB/km, 1.317 dB/km, 0.147 dB/km, and 0.687 dB/km. These two conditions are the main causes of transmission quality degradation in RoF-RoFSO hybrid systems. They can limit transmission distance from the FSO link. This study conducted a simulation on free space transmission distance from 100 m to 1000 m to review the effect of damping value on transmission distance on FSO link. It considers a range of distances every 100 m to see the limitation of transmission distance that occurs due to attenuation from atmospheric conditions from March 2022 to May 2022.

After going through the transmission media, the modulated optical system will be detected and converted back into an electrical signal by the photodetector PIN *in* the RRU. Then, the electrical signal will go through a filter-to-filter noise from the signal and then be forwarded to the OFDM Demodulator to be converted into symbols in the frequency domain (M-ary signal). These symbols are then passed through the QAM/PSK Sequence Decoder to be converted into binary form and characterized based on EVM and BER parameters to determine overall system performance. The BER value is obtained by comparing binary signals transmitted to the device under test (DUT) with binary signals received by the BER Test Set. Among others, the EVM value is obtained based on the magnitude of the change or shift in the constellation point after the signal is transmitted from the ideal constellation point received by the OFDM demodulator. The EVM value is represented as a percentage. Table 3 shows component specifications in the receiver.

Table 2. Fiber optic specification [31]

Specifications	Value
Fiber Length (L)	10 km
Fiber Attenuation (α_f)	0.17 dB/km
Fiber Dispersion	16.5 ps/nm/km
Wavelength	1550 nm

IV. Results and Analysis

The presented Hybrid RoF and RoFSO system is an investigation using optisystem simulation software. The performance is evaluated based on meteorological factors such as rain, dust, and haze, which are the main factors affecting signal degradation in the atmosphere. These meteorological effects will influence the maximum transmission distance that can be transmitted by optical signals in the atmosphere. The EVM will be a parameter used to determine the overall performance of the Hybrid RoF-RoFSO system. The EVM value standards set by 3GPP were 17.5% for QPSK, 12.5% for 16-QAM, and 8% for 64-QAM [34].

Figures 3-5 present the EVM values at maximum

Table 3. Optical receiver specification [33]

Specifications	Value
Photo Detector	PIN
Photo Detector Responsivity	0.85 A/W
Electrical Filter	Bandpass Bessel filter
Frequency cutoff	1.5 * bit rate

rainfall conditions from March 2022 to May 2022. In March 2022, the damping value for rain conditions was 11.52 dB/km. Figure 3 shows the maximum transmission distance of FSO is 700 meters for QPSK and 16-QAM modulation schemes with EVM values of 12.51% and 10.7%, respectively. In comparison, in the 64-QAM modulation scheme, the maximum distance of FSO is 600 m with EVM 7.02%.

In April 2022, the damping value was 16.35 dB/km. Figure 4 shows the maximum transmission distance of FSO is 600 meters for QPSK and 16-QAM modulation schemes, with EVM values of 13.76% and 11.59%, respectively. Meanwhile, in the 64-QAM modulation schemes, the maximum distance of FSO is 500 m, with EVM 6.79%. In May 2022, the damping value was 11.7 dB/km. Figure 5 shows the maximum transmission distance of FSO is 700 meters for QPSK and 16-QAM modulation schemes with EVM values of 12.78% and 10.7%, respectively. Meanwhile, in the 64-QAM modulation schemes, the maximum distance of FSO is 600 m with EVM 7.02%.

Figures 6-8 present the EVM values in dust and haze under minimum visibility from March 2022 to May 2022. In March 2022, the damping value for dust and haze was 0.986 dB/km. Figure 6 shows the maximum transmission distance of FSO is 1000 meters for QPSK, 16-QAM, and 64-QAM modulation schemes with EVM values of 6.5%, 6.13%, and 6.19%, respectively.

In April 2022, the damping value was 1.317 dB/km. Figure 7 shows the maximum transmission distance of

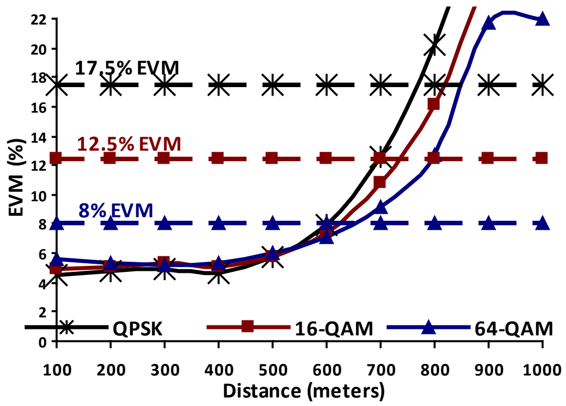

Figure 3. EVM results on rainy conditions in March

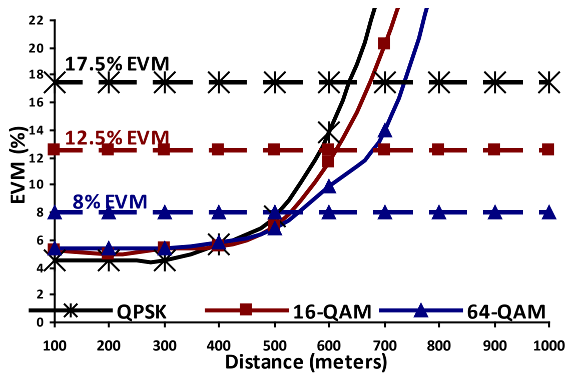

Figure 4. EVM results on rainy conditions in April

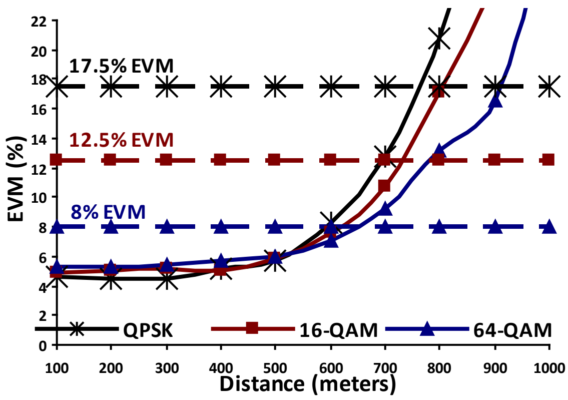

Figure 5. EVM results on rainy conditions in May

FSO is 1000 meters for QPSK, 16-QAM, and 64-QAM modulation schemes with EVM values of 6.68%, 6.38%, and 6.21%, respectively. In May 2022, the damping value was 0.687 dB/km. Figure 8 shows the maximum transmission distance of FSO is 1000 meters for QPSK, 16-QAM, and 64-QAM modulation schemes with EVM values of 6.52%, 6.01%, and 6.12%, respectively.

Table 4 and Table 5 show maximum transmission distance result comparison based on BER and EVM values with QPSK, 16-QAM, and 64 QAM modulation schemes in rain, haze, and dust conditions from March 2022 to May 2022. EVM and BER are parameters that indicate the quality of the communication system. The

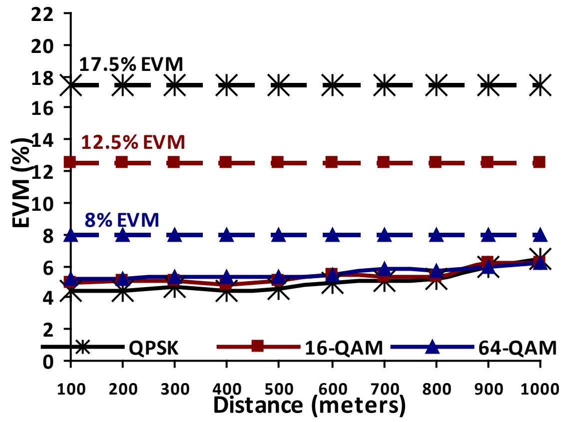

Figure 6. EVM results on dust and haze conditions in March

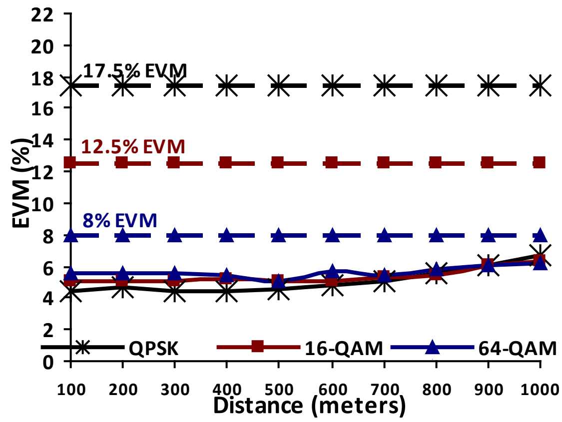

Figure 7. EVM results on dust and haze conditions in April

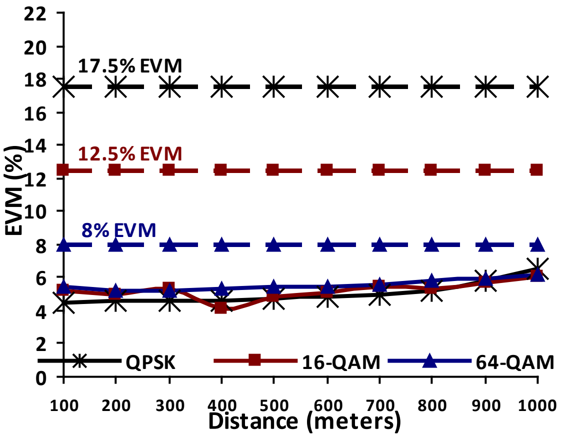

Figure 8. EVM results on dust and haze conditions in May

EVM indicates the change or shift of the constellation point from its ideal point after the signal is transmitted over the optical fiber and FSO link. Meanwhile, BER indicates the number of bits that experience errors when transmitted over fiber optics and FSO links. The more bits that experience errors, the higher the BER value. The EVM has an inverse square root proportionality with SNR, while SNR has a relationship with BER. The higher the SNR value, the lower the probability of an error in reading the bits in the receiver, so that the BER value will be lower. If the EVM and BER values obtained exceed the permissible standard values, then the quality of the RoF-RoFSO hybrid system can be bad. EVM values that exceed the minimum standard indicate the greater the distance between constellation points measured by constellation points ideally. The greater the distance between the measured constellation point and the ideal constellation point causes, the greater the error in the receiver in reading between one symbol and another. The higher the receiver error in reading the received symbol, the more bit values will experience errors because digital modulation consists of several bits in one symbol. Likewise, with the BER value, when the BER value exceeds the minimum standard, it indicates that many errors occur when bits of information are transmitted, resulting in the information sent by the transmitter cannot be received and read correctly by the receiver.

The minimum BER standards for QPSK and QAM modulation were 10^{-3} [35], while the EVM value standards set by 3GPP were 17.5% for QPSK, 12.5% for 16-QAM, and 8% for 64-QAM [34]. Suppose the EVM and BER values obtained on the receiver side meet the specified standards. In that case, the receiver can properly and correctly receive the quality of the information transmitted. However, if the minimum EVM and BER values are not met, the receiver cannot receive the information sent properly and correctly, so the system's quality is poor. This error in reading symbols and bits causes a limited transmission distance that optical signals in the FSO link can achieve. The longer the FSO transmission distance, the greater the attenuation value of the atmosphere in the air.

Atmosphere attenuation occurs due to losing some or all of the energy when transmitted through the atmosphere. So the atmosphere causes degradation and attenuation of signals caused by absorption, scattering, and scintillation. This research analyzes the performance of the RoF-RoFSO hybrid system based on atmospheric attenuation values caused by meteorological factors, namely rain and smog and dust. These two factors are the main factors causing the high attenuation value of the atmosphere, especially in tropical areas. In rainy conditions, the optical signal emitted by the laser will hit raindrops in the air and cause signal scattering. In conditions of smog and dust, optical signals are blocked by small particles in the air. When an optical signal is transmitted and hits the particle, the transmitted signal will also experience light scattering. This light scattering causes signal spread and weakens the transmitted signal, limiting the distance on the FSO link. This study determined the attenuation value in rainy conditions based on the Carbonneau model. In haze and dust conditions, the attenuation value of the atmosphere was calculated using the Kim model. From the calculations, the highest damping value in rainy conditions occurred in April 2022, where the damping value was 16.35 dB, while the highest damping value in haze and dust conditions was 1.317 dB, which occurred in April 2022.

Table 4 shows that in light rain conditions, the three modulation schemes can meet the BER 10^{-3} and EVM standards of 17.5% for QPSK, 12.5% for 16-QAM, and 8%. So that in light rain conditions, the three modulation schemes can reach a maximum transmission distance of up to 1000 m in the period March 2022 – May 2022. In moderate rain conditions, the BER and EVM values obtained with the QPSK and 16-QAM modulation schemes can meet the standard up to a maximum distance of 1000 m from March 2022 – May 2022. However, in moderate rain conditions, the 64-QAM modulation scheme can only meet EVM and BER standards up to a maximum distance of 1000 m in March 2022. Meanwhile, in April 2022, EVM and BER standards can only be met up to a transmission distance

Table 4. Simulation and calculation comaprison of received power at a transmission distance of 5 km

Period	Precipitation (mm)	Damping Value (dB)	Maximum Transmission Distance (m)		
			QPSK	16-QAM	64-QAM
March 2022	0.2	0.367	1000	0.2	0.367
	6.28	3.68	1000	6.28	3.68
	34.5	11.53	700	34.5	11.53
April 2022	0.4	0.58	1000	0.4	0.58
	11.75	5.6	1000	11.75	5.6
	54	16.35	600	54	16.35
May 2022	0.2	0.367	1000	0.2	0.367
	8.8	4.62	1000	8.8	4.62
	35.2	11.7	700	35.2	11.7

of 800 m, while in May 2022, the maximum transmission distance is only up to 900 m. In heavy rain conditions, the maximum transmission distance that meets EVM and BER standards with the QPSK and 16-QAM modulation schemes is 700 m in March 2022 and May 2022, while in April 2022, the maximum transmission distance that meets EVM and BER standards is 600 m. Meanwhile, the 64-QAM modulation scheme can be met for maximum transmission distances of up to 600 m in March 2022 and May 2022 and 500 m in April 2022.

Based on the simulation results in rainy conditions, the 64-QAM modulation scheme's maximum transmission distance is more limited when compared to the QPSK and 16-QAM modulation schemes. This condition happens because the use of modulation order in the 64-QAM scheme is higher when compared to the QPSK and 16-QAM modulation schemes. As the modulation order increases, the distance between the constellation points gets closer, allowing for higher bit and symbol errors due to interference when the signal is transmitted in the atmosphere [20], [32], [36], [37]. Research [38]-[39] also shows that using a high degree of modulation can improve the spectral efficiency corresponding to 5G systems. However, increasingly higher modulation orders make it more susceptible to noise and errors during signal transmission.

Table 5 shows that attenuation due to haze and dust conditions do not significantly affect quality degradation based on EVM and BER standards. The maximum transmission distance that meets EVM and BER standards for the three modulation schemes used is 1000 m from March 2022 to May 2022. Based on all simulation results, attenuation due to rainfall is more influential in limiting the transfer distance at the FSO link compared to attenuation due to haze and dust. The damping value due to rain can limit the transmission distance to 500 m with the 64-QAM modulation scheme in April 2022, while the damping value in haze and dust conditions can reach a transmission distance of up to 1000 m for the three modulation schemes used from March 2022 to May 2022. Therefore, in implementing a hybrid RoF-RoFSO system in urban areas, the meteorological effects of rain, smog, and dust must be considered. Rainy conditions and smog and dust have different influences on the performance of hybrid RoF-RoFSO systems. The meteorological effect of rain is the main factor that causes limited distance in the FSO link. Moreover, differences in rainfall significantly limit the transmission distance, whereas, in heavy rain conditions, the FSO link transmission distance is reduced by up to 50% compared to light rain conditions.

Table 5. Comparison of received power at a transmission distance of 10 km

Period	Visibility (km)	Damping Value (dB)	Maximum Transmission Distance (m)		
			QPSK	16-QAM	64-QAM
March 2022	2	0.986	1000	1000	1000
	7.1	0.143	1000	1000	1000
	10	0.101	1000	1000	1000
April 2022	1.6	1.317	1000	1000	1000
	6.9	0.147	1000	1000	1000
	10	0.101	1000	1000	1000
May 2022	2.6	0.687	1000	1000	1000
	6.9	0.147	1000	1000	1000
	10	0.101	1000	1000	1000

V. Conclusion

A hybrid radio over fiber (RoF) and radio over free space optic (RoFSO) system has been designed with QPSK, 16-QAM, and 64-QAM modulation schemes for implementing 5G fronthaul networks in Indonesia. The design considered two conditions caused by the meteorological effects of rain, smog, and dust. These two meteorological effects are the main causes of signal degradation on the FSO link. In heavy rain conditions, the maximum transmission distance is the RoF-RoFSO hybrid system with the QPSK and 16-QAM modulation schemes is 600 m. The maximum transmission distance is 500 m using the 64-QAM modulation scheme. Meanwhile, all three modulation schemes can reach the maximum transmission distance of 1000 m in haze and dust conditions. This research can provide an understanding of the influence of atmospheric attenuation caused by weather conditions in Indonesia on the performance of the RoF-RoFSO hybrid system so that it can provide an overview in implementing the RoF-RoFSO hybrid system as a fronthaul network on 5G technology.

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