Indonesian Journal of Electrical Engineering and Computer Science
Vol. 36, No. 3, December 2024, pp. 1543~1554
ISSN: 2502-4752, DOI: 10.11591/ijeecs.v36.i3.pp1543-1554

Outage analysis of a single-threshold hard-switching hybrid FSO/RF system for reliable pico-macrocell backhauling

Abduljalal Yusha'u Kassim[1], Vitalice Kalecha Oduol[2], Aliyu Danjuma Usman[3]
[1]Department of Electrical Engineering, Pan African University Institute for Basic Sciences, Technology and Innovation (PAUSTI), Nairobi, Kenya
[2]Department of Electrical and Information Engineering, Faculty of Engineering, University of Nairobi, Nairobi, Kenya
[3]Department of Electronics and Telecommunications Engineering, Faculty of Engineering, Ahmadu Bello University, Zaria, Nigeria

Article Info

Article history:

Received May 15, 2024
Revised Aug 8, 2024
Accepted Aug 26, 2024

Keywords:

Gamma-gamma distribution
Hard-switching
Hybrid FSO/RF
Outage probability
Pico-macrocell backhauling
Rician fading distribution
Single-threshold

ABSTRACT

In the quest for high-speed, reliable and cost-effective backhaul solutions for modern cellular networks, the hybrid free space optical (FSO) and radio frequency (RF) communication system is envisaged to be a promising technology. The hybrid system merges the benefits of both RF and FSO subsystems, delivering high data rates and reliability. The integration of both technologies improves the communication system's performance by addressing the inherent limitations of each. This study proposes a single-threshold hard-switching hybrid FSO/RF system for reliable pico-macrocell backhauling applications. We formulated closed-form expressions for the cumulative density functions (CDFs), probability density functions (PDFs), and outage probability (OP) for RF-only, FSO-only and hybrid FSO/RF links. The rician fading and gamma-gamma (G-G) channel distributions were utilized, respectively. The average received signal-to-noise ratio (SNR) determines the switching mechanism based on the defined threshold and atmospheric condition. Simulation results and analysis demonstrated that, at any average SNR above the defined threshold, the hybrid system's OP outperforms that of the RF-only and FSO-only links under most conditions. The analysis illustrates that employing the hybrid FSO/RF system enhances reliability and boosts overall system performance in pico-macrocell backhauling scenarios, surpassing the performance of standalone FSO-only or RF-only links.

Corresponding Author:

Abduljalal Yusha'u Kassim
Department of Electrical Engineering, Pan African University Institute for Basic Sciences
Technology and Innovation (PAUSTI)
PAUSTI complex block B, JKUAT main campus, Juja, P. O. Box 62000-00200 Nairobi, Kenya
Email: yushau.abduljalal@students.jkuat.ac.ke

1. INTRODUCTION

The escalating demands for high-speed mobile data traffic exert significant pressure on cellular networks regarding data rate, capacity and coverage. The proliferation of small cell networks, particularly picocells, within heterogeneous networks is seen as a feasible solution for addressing capacity and coverage issues in cellular networks [1], [2]. However, the anticipated extensive deployment of picocells in 5G and beyond networks, alongside conventional backhauling methods like fibre optics, microwave, or copper wire which can be costly or inefficient necessitates the exploration of alternative solutions. Fiber optics, while offering high capacity and reliability, suffer from high deployment costs and inflexibility, particularly in urban and densely populated areas. Conversely, microwave backhauling, although more cost-effective and easier to deploy, is susceptible to interference and congestion in the increasingly crowded electromagnetic spectrum. In search of better alternative solutions, the free space optical communication (FSOC) promises to solve many issues associated with traditional backhaul technologies, owing to its positive benefits including high data rate, free licensing, low costs, no permit requirements, interference-free, high confidentiality, low power needs, and less time required for installation and deployment [3]. FSOC technology's cost-effectiveness, flexibility, ease of deployment and maintenance motivate telecom operators to consider its potential for mobile backhauling [4], [5]. Although FSOC technology offers significant advantages, its performance can be negatively impacted by atmospheric conditions, such as turbulence causing scintillation, adverse weather conditions like rain, snow, haze, fog, misalignment due to building movements or mechanical vibrations between transceivers, and obstruction by airborne objects like birds or drones [6], [7].

To address these challenges and fully realize FSOC technology's potential, integrating it with RF technology at 60 GHz creates a hybrid free space optical/radio frequency (FSO/RF) system, offering high data rates and enhanced reliability [8], [9]. Hybrid FSO/RF communication leverage the strengths of both technologies, mitigating their individual limitations. While FSO communication offers high bandwidth and immunity to electromagnetic interference, it is highly sensitive to atmospheric conditions such as haze, rain, fog, and snow. On the other hand, RF communication provides robust performance under various weather conditions but suffers from limited bandwidth and interference issues. By integrating these two complementary technologies, hybrid FSO/RF systems aim to ensure reliable and high-capacity backhaul links for pico-macrocell backhauling, which is very crucial for modern cellular networks.

The hybrid FSO/RF communication system employs either soft-switching or hard-switching mechanisms. For hard-switching, FSO and RF links operate in parallel, switching only when one link's signal-to-noise ratio (SNR) falls below a threshold. Soft-switching involves simultaneous operation of both links, utilizing diversity techniques at the receiver. However, soft-switching suffers from power and spectrum resource inefficiencies, as well as complexity in receiver design, compared to hard-switching. While previous works have explored hybrid FSO/RF systems, this research specifically proposes and analyzes a single-threshold hard-switching mechanism. This design choice simplifies the switching process compared to more complex adaptive or multiple-threshold systems, aiming to achieve a balance between performance and implementation complexity.

In the literature, the soft-switching technique with different combining methods is adopted in [10]-[17]. Kazemi *et. al.* [10] employed soft-switching scheme to evaluate the probability of outage of a hybrid system. This method allows activation of either or both links as per availability. By applying the finite-state-Markov-chain (FSMC) technique, they developed a model to select suitable links for switching based on the changing meteorological conditions. Numerical analysis of the scheme demonstrates the system's outage performance under various weather scenarios. Rakia *et al.* [11] introduced and investigated an adaptive combining scheme for data transmission for a hybrid communication system. For SNR above a specified threshold, the FSO link remains active; otherwise, transmission is done on both links and combined by dual-branch maximal ratio combining at the receiving end. A new expression for the system's outage performance was derived from the received SNR’s cumulative density function (CDF). Simulations recommends the adaptive combining technique for the hybrid system, and performs better in terms of outage probability (OP) under various weather conditions and levels of atmospheric turbulence. The study described in [12] put forward a unique switching strategy for hybrid systems that adaptively toggles the RF and FSO links based on the prevailing channel conditions in real-time. RF link, being susceptible to Rayleigh fading, employs a single threshold, while the FSO link, subject to severe atmospheric turbulence, uses two different threshold levels. Numerical analyses were conducted to evaluate the system's performance, specifically looking at OP and bit error rate (BER). Shakir [13] suggested an alternative design that operates independent of the need for channel state information. The same data is sent concurrently through both links. At the receiver's end, a selection combining scheme is used to merge the incoming signals. New expressions for OP and BER have been developed. Performance evaluation demonstrates superiority of the introduced hybrid system over a standalone FSO link. Tokgoz *et al.* [14], an innovative selection technique utilizing index modulation (IM) without transmitter feedback or channel state information was proposed for FSO-mmWave systems. This IM-based mechanism was evaluated against traditional switching methods across varied conditions. Numerical analyses and simulations illustrate significant enhancements in overall system performance, particularly in spectral efficiency and BER. Wu *et. al.* [15] conducted an extensive investigation on security and communication aspects for a hybrid FSO/RF system, adopting α-m and Málaga channel distributions. Maximum ratio combining (MRC) was utilized as a diversity technique for signal reception. Simulation outcomes demonstrate notable improvements in communication performance compared to the FSO-only system. A machine learning (ML) algorithm was employed in [16] to explore the modulation adaptation mechanism in hybrid systems. Hybrid link budgets were estimated across different modulations and environmental scenarios, notably severe weather conditions. Accuracy testing of switching and modulation adaptation was conducted, with a focus on rain and fog. Simulation outcomes indicate promising performance of the proposed algorithm. Liang *et al.* [17], the hybrid relay system was developed using a relay approach of decode-and-forward. Employing adaptive combining scheme, users access the network via the THz link. Analytical expressions for OP and BER were formulated using statistical characteristics of the links. Analysis reveals that the proposed system, incorporating the adaptive combining scheme, can enhance both BER and OP, thereby improving communication rate while maintaining reliability.

Studies on the hard-switching technique using received SNR threshold for switching between links are conducted Researchers in [18]-[24]. Usman *et. al.* [18] introduced and scrutinized a switching-based technique for a hybrid FSO/RF communication system. This scheme activates either of the links at any moment, with preference to the FSO link using single and dual-threshold scenarios. Expressions were derived for ergodic capacity, OP and average BER, and evaluated. Numerical findings demonstrate substantial performance improvements of the scheme as compared to standalone FSO-only configurations. Touati *et al.* [19] analyzed the impact of path loss, along with atmospheric and alignment issues, on the performance of hybrid FSO/RF systems. Closed-form expressions for probability of outage and BER for both links were derived. The FSO link utilized gamma-gamma (G-G) distribution and OOK modulation, while rician channel fading operated at 60 GHz frequency with 16-QAM modulation for the RF link. Simulation results indicate that hybridization can mitigate vulnerabilities of FSO links to atmospheric disturbances and misalignment fading. Ghoname *et al.* [20], an investigation was conducted on the operations of an adaptive hybrid system operating across various wavelengths and frequencies for FSO and RF links respectively, specifically in conditions influenced by fog, humidity, and rain. Performance evaluation, based on received power and BER measurements, aimed to identify optimal wavelengths and frequencies to minimize attenuation and ensure reliable signal delivery under varying atmospheric conditions. Results highlight the effectiveness of using a 1,550 nm wavelength for the FSO link in enhancing system performance.

Khalid *et al.* [21] examined the operation of hard-switching scheme in wireless networks. Where only one link is active at any given time, prioritizing the FSO link. When the FSO link's SNR falls below a set threshold, the RF link is activated. The study assumed G-G fading and rayleigh fading for the FSO and RF links respectively. Analytical formulas were developed to assess the hybrid model's ergodic capacity, BER and OP. Comparisons was made between the hybrid model and a standalone FSO model to evaluate performance. Vishwakarma and Swaminathan [22], a detailed performance analysis was conducted on a hybrid FSO/RF system, that utilized a single-threshold-based switching strategy applicable to both satellite and terrestrial communication scenarios. The FSO link is described by a generalized Malaga distribution, considering factors such as atmospheric attenuation and misalignment errors. In contrast, the RF channel's fading is represented by the generalized κ-μ-η distribution. Unified closed-form equations were formulated to calculate the OP, average symbol error rate, and ergodic capacity of the hybrid system by employing methods like heterodyne detection and IM/DD. The hybrid system with its RF backup link using Monte Carlo simulations outperformed standalone FSO systems, especially under conditions of severe turbulence, notable pointing errors, and challenging weather. In their analysis, Magidi and Jabeena [23] analyzed a hybrid FSO/RF communication system performance employing a Malaga distribution alongside a multi-pulse position modulation scheme, and a rician distribution using 16 QAM modulation. New equations were developed to calculate the OP and BER for the RF, FSO, and the integrated hybrid FSO/RF systems. The findings indicated that a lower normalized jitter standard deviation was associated with better OP, independent of the turbulence level. This highlights the benefits of the hybrid RF/FSO approach across different operational conditions. Nikbakht-Sardari *et al.* [24], two innovative hybrid RF/FSO system designs were proposed, featuring hard-switching mechanisms to tackle misalignment errors and atmospheric turbulence. The first configuration consists of a hybrid relay-based RF-FSO link and a standalone RF link. The second configuration includes an FSO link combined with a relay-based RF-FSO link, both operating simultaneously. These setups utilize a dual-threshold SNR approach to prolong the primary path's lifespan, with a hard switch determining the transmission route based on these thresholds. The RF and FSO links were modeled using rayleigh and G-G distributions, respectively, and closed-form expressions for OP are derived. Both configurations employ intensity modulation with direct detection and heterodyne detection methods. Numerical analysis under different atmospheric conditions and misalignment errors scenarios confirmed the proposed designs' effectiveness. Kassim *et al.* [25] proposed, designed, and assessed a 350 m FSOC link's performance for backhauling from picocells to macrocell across diverse atmospheric conditions. Evaluation criteria included quality factor, eye diagrams and BER analysis. Results indicated the feasibility of deploying the FSOC link for such application. The designed link exhibited robust performance in various environmental conditions, including clear skies with/out turbulence, wet snow, fog, haze and heavy rain.

This paper focuses on developing an efficient switching algorithm, a configuration that switches between FSO or RF links based on a predefined SNR threshold. The single-threshold mechanism is designed to simplify the switching process and enhance system reliability. By thoroughly analyzing the outage performance using different received SNR thresholds and system parameters, we aim to provide solution into optimizing hybrid FSO/RF systems for efficient, cost-effective and reliable pico-macrocell backhauling. Also, with the goal to highlight the potentials of hybrid FSO/RF systems in addressing backhauling challenges in next-generation cellular networks and to propose strategies for their effective implementation. The contributions of this paper include: i) designing the hybrid FSO/RF deployment scenario concept for pico-macrocell backhauling application; ii) we formulate the PDF and CDF expressions for the RF and FSO links, respectively; iii) we obtained the OP equations for RF-only, FSO-only and hybrid FSO/RF system; iv) we proposed an algorithm flowchart for the implementation of a single-threshold hard-switching scheme; v) using MATLAB simulations, we conducted numerical analysis of the proposed scheme and evaluated the probability of outage for the links; and vi) finally, we demonstrated the significant improvement offered by the hybrid system in terms of OP as compared to standalone FSO-only or RF-only links. The organization of the paper is as follows: section 2 covers the system and channel models, section 3 details the results and discussions, and section 4 concludes the paper.

2. SYSTEM AND CHANNEL MODEL

Section two presents the system and channel model, detailing the hybrid FSO/RF deployment scenario concept. It includes the formulation of the expressions for PDFs and CDFs for the RF and FSO links. Additionally, OP analysis equations are formulated for the RF, FSO, and hybrid FSO/RF system. A flowchart of the proposed single-threshold hard-switching scheme is designed for the links' switching operations.

2.1. System model

This subsection illustrates the system model, as presented in Figure 1. It depicts the hybrid system deployment scenario concept for pico-macrocell backhauling. It shows mobile users connected to a picocell and the picocell is backhauled to the macrocell via FSO or RF links. Priority is given to FSO link and is susceptible to atmospheric attenuation and turbulence. During strong turbulence or attenuation condition, data transmission is done via the RF link.

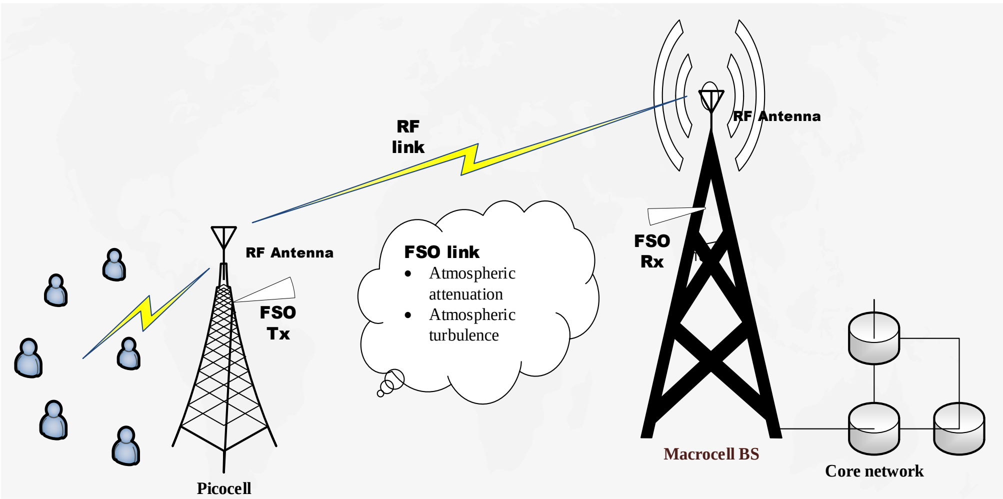


Figure 1. Hybrid FSO/RF deployment scenario concept for pico-macrocell backhauling

2.2. FSO link

Based on the FSO link designed in [25] for pico-macrocell backhauling applications, the FSO transceiver is in line-of-sight, no pointing/misalignment errors. The link operates using intensity modulation and direct detection with on-off keying modulation, at 1,550 nm optical wavelength, and link range of 350 m. At the receiver side, the received signal is given as:

$$r_1 = hS_1 + n_1 \tag{1}$$

where S_1 is the transmitted signals, n_1 denotes the additive white gaussian noise with zero mean and variance (AWGN), and h indicates normalized channel fading. With assumed point-to-point communication between the transceivers, the pointing errors/misalignment is considered negligible, especially for links below 1 km. Therefore, the normalized channel fading contains only the effects of the atmospheric attenuation as a result of absorption and beam scattering, and atmospheric turbulence as a result of scintillation. The atmospheric attenuation (h_a) is given by Beers-lambert law as [19]:

$$h_a = exp\ (-\propto d) \tag{2}$$

$$\propto = \frac{3.91}{V}\left(\frac{\lambda_{FSO}}{550}\right)^{-p} \tag{3}$$

where $\propto$ is attenuation coefficient, link distance indicated by d, V is the atmospheric visibility and p is scattering particle size distribution. The atmospheric turbulence (h_t) effects is a function of random fluctuation of the phase and intensity of the received signal. Considering G-G distribution at moderate to strong turbulence condition, it has a probability density function (pdf) as [21]:

$$f_{h_t}(h_t) = \frac{2(\alpha\beta)^{\frac{\alpha+\beta}{2}}}{\Gamma(\alpha)\Gamma(\beta)} h_t^{\frac{\alpha+\beta}{2}-1} K_{\alpha-\beta}\left(2\sqrt{\alpha\beta h_t}\right) \tag{4}$$

where the large and small-scale eddies of the scattering process are denoted by α and β respectively, $\Gamma(.)$ represent the Gamma function and $K_n(.)$ is the modified Bessel function of the second kind of order n. The specific parameters (α and β) of the scattering process are defined as follows [26]:

$$\alpha = \left\{exp\left(\frac{0.49\sigma_R^2}{\left(1+1.11\sigma_R^{12/5}\right)^{7/6}}\right) - 1\right\}^{-1} \tag{5}$$

$$\beta = \left\{exp\left(\frac{0.51\sigma_R^2}{\left(1+0.69\sigma_R^{12/5}\right)^{5/6}}\right) - 1\right\}^{-1} \tag{6}$$

where Rytov variance is denoted by σ_R^2, which is refractive index (C_n^2) dependent and is defined as [19]:

$$\sigma_R^2 = 1.23C_n^2\left(\frac{2\pi}{\lambda_{fso}}\right)^{7/6} d^{11/6} \tag{7}$$

The refractive index (C_n^2) determines the strength of the turbulences. The turbulence regimes are classified into strong (C_n^2=5.0×10^{-14}m$^{-2/3}$), moderate (C_n^2=1.7×10^{-14}m$^{-2/3}$), and weak (C_n^2=8.4×10^{-15}m$^{-2/3}$) turbulence conditions respectively [13]. In terms of received electrical SNR, the relationship between the instantaneous SNR (γ_{FSO}), average SNR $(\bar{\gamma}_{FSO})$ and the atmospheric turbulence fading coefficient (h_t) of the FSO link is given in (8a) and (8b). The average SNR $(\bar{\gamma}_{FSO})$ is given in (9) as [11]:

$$\gamma_{FSO} = \bar{\gamma}_{FSO} h_t^2 \tag{8a}$$

$$h_t = \sqrt{\frac{\gamma_{FSO}}{\bar{\gamma}_{FSO}}} \tag{8b}$$

$$\bar{\gamma}_{FSO} = \frac{\eta^2\mu^2 E_s P_{FSO}^2 \alpha_{FSo}^2}{\sigma_{FSO}^2} \tag{9}$$

where η is the photo-detector responsivity, μ denotes modulation index, E_s represents the average symbol energy, P_{FSO} is the transmitted optical power, σ_{FSO} defines the shot-noise variance which arises from photo detection process, and α_{FSO} is the optical power attenuation defined in (2) and (3). In terms of the instantaneous and average SNR of the FSO link, and applying power transformation of random variables, the PDF in (4) can be presented as:

$$f_{\gamma_{FSO}}(\gamma_{FSO}) = \frac{\left(\alpha\beta/\sqrt{\bar{\gamma}_{FSO}}\right)^{\frac{\alpha+\beta}{2}}}{\Gamma(\alpha)\Gamma(\beta)} \gamma_{FSO}^{\frac{\alpha+\beta}{4}-1} K_{\alpha-\beta}\left(2\sqrt{\alpha\beta\sqrt{\frac{\gamma_{FSO}}{\bar{\gamma}_{FSO}}}}\right),\ \gamma_{FSO} \geq 0 \tag{10}$$

In terms Meiger G-function, the Bessel function, $K_{\alpha-\beta}[.]$ can be expressed using (14) in [27] and (3) in [11], (10) can be reduced to:

$$f_{\gamma_{FSO}}(\gamma_{FSO}) = \frac{{\gamma_{FSO}}^{-1}}{2\Gamma(\alpha)\Gamma(\beta)} G_{0,2}^{2,0}\left(\alpha\beta\sqrt{\frac{\gamma_{FSO}}{\bar{\gamma}_{FSO}}}\middle|_{\alpha,\ \beta}^{-}\right) \tag{11}$$

By integrating and simplifying the PDF in (11), the CDF of the SNR for the G-G distribution FSO link is presented as [11]:

$$F_{\gamma_{FSO}}(\gamma_{FSO}) = \frac{2^{\alpha+\beta-2}}{\pi\Gamma(\alpha)\Gamma(\beta)} G_{1,5}^{4,1}\left(\frac{(\alpha\beta)^2}{16\bar{\gamma}_{FSO}}\gamma_{FSO}\ \middle|_{\frac{\alpha}{2},\ \frac{\alpha+1}{2},\ \frac{\beta}{2},\ \frac{\beta+1}{2},\ 0}^{1}\right) \tag{12}$$

2.3. RF link

The proposed backup RF link utilizes the millimeter wave carrier frequency operating at 60 GHz. The link is assumed to be a line-of-sight communication channel and quadrature modulation, and thus is modeled as a rician distribution. This fading model is the best fit for strong direct line-of-sight communication between the transceivers. The link average power gain is given as [19]:

$$h_p[dB] = G_T^{RF} + G_R^{RF} - 20\,log_{10}\frac{4\pi d}{\lambda_{RF}} - \alpha_{oxy}d - \alpha_{rain}d \tag{13}$$

where gains of the transmitting and receiving antennas are denoted by G_T^{RF} and G_R^{RF} respectively. λ_{RF} is the mmW operating wavelength, α_{rain} and α_{oxy} characterizes the attenuation coefficients due to rain scattering and oxygen absorption, respectively. d is the distance between the transceivers. At the receiver side, the RF signal received is given as [23]:

$$r_{RF} = \sqrt{h_p}h_f S + n_o \tag{14}$$

where S denotes the transmitted signal, h_p and h_f represent the RF links' path loss and fading coefficients, respectively. The noise term shown as n_o is assumed to be AWGN with complex zero mean and variance $\sigma_n^2 = E[n_o^2]$. Based on the rician fading distribution, the RF link's PDF is given as [26]:

$$f_{RF}(h_f) = 2(1+K)h_f\left(-K - (1+K)h_f^2\right) \times I_o\left(2h_f\sqrt{K(1+K)}\right) \tag{15}$$

Here, K is the rice parameter, representing the strength of the direct line-of-sight component in the fading coefficient. A low K value denotes severe channel fading, with K=0 indicating the largest fading scenario, also known as rayleigh fading-a subset of the rician fading model. Higher values of K indicate less fading, with the highest values associated with the AWGN. I_o is the zeroth-order modified Bessel function of the first kind. In (16a) and (16b) shows the relationship between the RF link's instantaneous received SNR (γ_{RF}) as a function of the average SNR ($\bar{\gamma}_{RF}$) and h_f denote the fading coefficient:

$$\gamma_{RF} = \bar{\gamma}_{RF}h_f^2 \tag{16a}$$

$$h_f = \sqrt{\frac{\gamma_{RF}}{\bar{\gamma}_{RF}}} \tag{16b}$$

Using the instantaneous and average SNR representation, the PDF of the Rician fading channel can be rewritten by substituting (16b) into (15) and after some simplifications, $f_{RF}(h_f)$ is expressed as:

$$f_{\gamma RF}(\gamma_{RF}) = \frac{K+1}{\bar{\gamma}_{RF}}\ exp\left[-(K+1)\frac{\gamma_{RF}}{\bar{\gamma}_{RF}} - K\right] \times I_o\left(2\sqrt{K(K+1)\frac{\gamma_{RF}}{\bar{\gamma}_{RF}}}\right) \tag{17}$$

The CDF of the instantaneous SNR of the RF link can be given as [10] and [28] in (18), where $Q_1[.,.]$ is the Marcum function of the first order:

$$F_{\gamma RF}(\gamma_{RF}) = 1 - Q_1\left(\sqrt{2K},\ \sqrt{2(K+1)\frac{\gamma_{RF}}{\bar{\gamma}_{RF}}}\right) \tag{18}$$

2.4. Single-threshold hard-switching mechanism

The hybrid system, tailored for pico-macrocell backhauling as illustrated in Figure 1, comprises FSO link as the primary link and RF link as a backup. A single-threshold hard-switching scheme is proposed for link switching, considered to be most effective and economical for this application scenario. The FSO link handles data transmission when its instantaneous SNR (γ_{FSO}) exceeds a specified threshold (γ_{th}^{FSO}). If atmospheric conditions deteriorates or blockage occurs, causing the FSO link's SNR to drop below this threshold, the system triggers the backup RF link. Data transmission is done via the RF link, if it's instantaneous SNR (γ_{RF}) surpasses the RF threshold (γ_{th}^{RF}). When both links' SNR falls below their respective thresholds, the system enters an outage state. Figure 2 illustrates the switching operation of the single-threshold hard-switching scheme. Additionally, Figure 3 depicts the algorithm flowchart governing single-threshold hard-switching operation.

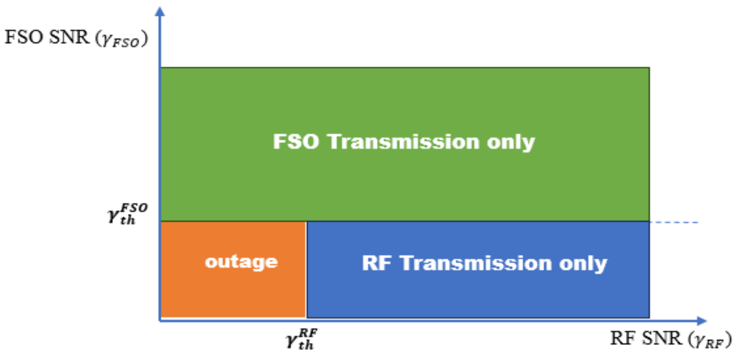


Figure 2. Single-threshold switching operation

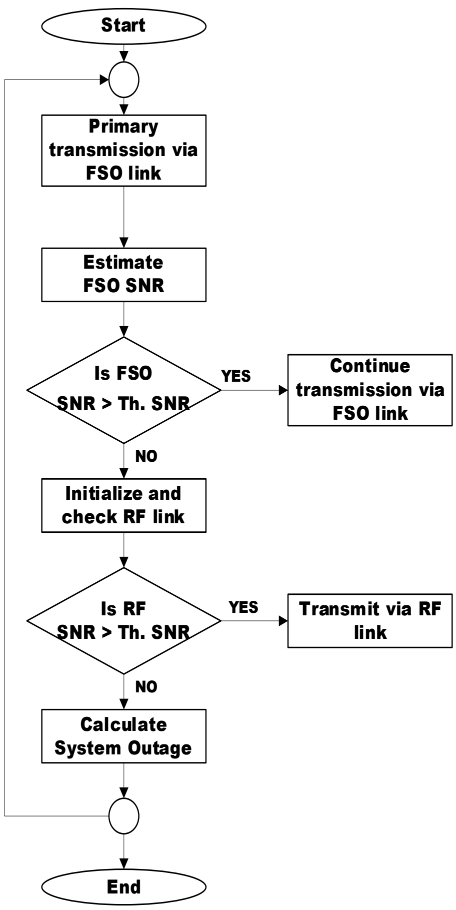


Figure 3. Algorithm flowchart for the proposed Hybrid FSO/RF system

2.5. Analysis of the probability of outage for the hybrid FSO/RF system

Among the key performance indicators (KPI) of a wireless communications system is the outage probability. It can be defined as a condition where the received SNR drops below a defined threshold, which affects the reliability and quality of transmission. Therefore, the system is declared in outage and cannot transmit data. The OP for the RF, FSO and finally hybrid FSO/RF system are deduced in (19)–(25).

The FSO link's OP is derived by evaluating its CDF in (12) and is given as:

$$P_{out}^{FSO}(\gamma_{th}^{FSO}) = P(\gamma_{FSO} < \gamma_{th}^{FSO}) = F(\gamma_{th}^{FSO}) \quad (19)$$

where γ_{th}^{FSO} denotes the FSO link's threshold SNR and $F(.)$ represent the CDF and is defined as:

$$F(\gamma_{th}^{FSO}) = \int_0^{\gamma_{th}^{FSO}} f_{\gamma_{FSO}}(\gamma_{FSO}) d\gamma_{FSO} \quad (20)$$

Simplifying (19) by substituting (12) in (20), the FSO link's OP is expressed by replacing instantaneous SNR (γ_{FSO}) with the threshold SNR (γ_{th}^{FSO}) in the link's CDF [13] and is given as:

$$P_{out}^{FSO}(\gamma_{th}^{FSO}) = \frac{2^{\alpha+\beta-2}}{\pi\Gamma(\alpha)\Gamma(\beta)} G_{1,5}^{4,1}\left(\frac{(\alpha\beta)^2}{16}\frac{\gamma_{th}^{FSO}}{\bar{\gamma}_{FSO}}\middle|\begin{matrix}1\\ \frac{\alpha}{2}, \frac{\alpha+1}{2}, \frac{\beta}{2}, \frac{\beta+1}{2}, 0\end{matrix}\right) \quad (21)$$

The outage probability for the RF link is derived by evaluating its CDF in (18) and is given as:

$$P_{out}^{RF}(\gamma_{th}^{RF}) = P(\gamma_{RF} < \gamma_{th}^{RF}) = F(\gamma_{th}^{RF}) \quad (22)$$

Therefore, substituting (18) in (22) and some simplification gives:

$$P_{out}^{RF}(\gamma_{th}^{RF}) = 1 - Q_1\left(\sqrt{2K}, \sqrt{2(K+1)\frac{\gamma_{th}^{RF}}{\bar{\gamma}_{RF}}}\right) \quad (23)$$

Finally, outage analysis of the hybrid system is derived from (21) and (23). This state occurs when the SNRs of both links fall below their respective thresholds, resulting in a complete system outage. The probability of outage of the hybrid FSO/RF is given as:

$$P_{out}^{hybrid} = P_{out}^{FSO}(\gamma_{th}^{FSO}) \times P_{out}^{RF}(\gamma_{th}^{RF}) \quad (24)$$

Substituting (21) and (23) into (24), gives:

$$P_{out}^{hybrid} = \frac{2^{\alpha+\beta-2}}{\pi\Gamma(\alpha)\Gamma(\beta)} G_{1,5}^{4,1}\left(\frac{(\alpha\beta)^2}{16}\frac{\gamma_{th}^{FSO}}{\bar{\gamma}_{FSO}}\middle|\begin{matrix}1\\ \frac{\alpha}{2}, \frac{\alpha+1}{2}, \frac{\beta}{2}, \frac{\beta+1}{2}, 0\end{matrix}\right) \times \left[1 - Q_1\left(\sqrt{2K}, \sqrt{2(K+1)\frac{\gamma_{th}^{RF}}{\bar{\gamma}_{RF}}}\right)\right] \quad (25)$$

Using the formulated CDF and PDF expressions of the RF and FSO links in (10), (12), (17), and (18) respectively, and the respective OP of the FSO, RF and hybrid FSO/RF derived in (21), (23), and (25), and the proposed single-threshold hard-switching mechanism, using MATLAB simulations, the performance of the hybrid system is evaluated in section three.

3. RESULTS AND DISCUSSION

The simulation results obtained from the study and their discussion is presented in this section. Also, implications and applications of the findings are presented. Based on the proposed system and channel model in section 2, the formulated expressions of the OP for the RF-only, FSO-only and hybrid FSO/RF links, the performance of the proposed switching algorithm is evaluated. Utilizing rician fading and G-G distribution for the respective RF and FSO links, and considering a strong turbulence condition with $\alpha = 2.064$ and $\beta = 1.342$, and an atmospheric attenuation of 0.233 dB/km for a clear sky weather condition. A rice parameter of K=6 dB is used for the RF link. A link distance of 350 m is considered which is best fit for pico-macrocell backhauling distance. Graphs of the probabilities of outage for the RF-only, FSO-only and hybrid FSO/RF links are achieved via MATLAB simulations considering the stated conditions.

Figure 4 presents the plot of OP against average SNR for single-threshold FSO-only, RF-only and hybrid FSO/RF. Based on the condition that a link only goes on outage for average SNRs below a specified threshold which is dependent on the quality of service. For the FSO link, a threshold of γ_{th}^{FSO}=6 dB and γ_{th}^{RF} =3 dB for the RF link are evaluated. From the graph, it is observed that the OP of both links decreases with an increase in average SNR, this is as a result of better signal quality at higher SNR. The FSO-only link goes on outage for SNR below 6 dB and RF-only link goes on outage for SNR below 3 dB.

The for the hybrid system illustrates the combined benefits of hybridizing FSO and RF links, where the FSO link is in outage at SNR below 6 dB, the RF link continue to transmit the data, thus providing a reliable and consistent operation of the system. This clearly depicts the case were the FSO link being subjected to severe attenuation or severe turbulence or even blockage by objects and its SNR goes below the threshold, then the RF link comes in to continue data transmission, thus improving the reliability of the deployment particularly for pico-macrocell backhauling applications.

The plot for OP against average SNR for single-threshold RF-only, FSO-only and hybrid FSO/RF is presented in Figure 5. The same threshold of γ_{th}^{FSO}=γ_{th}^{RF} =6 dB for both links is considered. At the same SNR threshold of 6 dB, it gives clearer understanding of the operation of the algorithm. The hybrid system goes on outage since both links are in outage at SNR below 6 dB. If any of the link's SNR improves above 6 dB threshold, the hybrid system is declared non-outage. The switching between the links based on real time SNR evaluations can effectively minimize the total system OP, thus making it highly suitable for the said deployment scenario where primary FSO link failure can lead to significant operational disruptions of service.

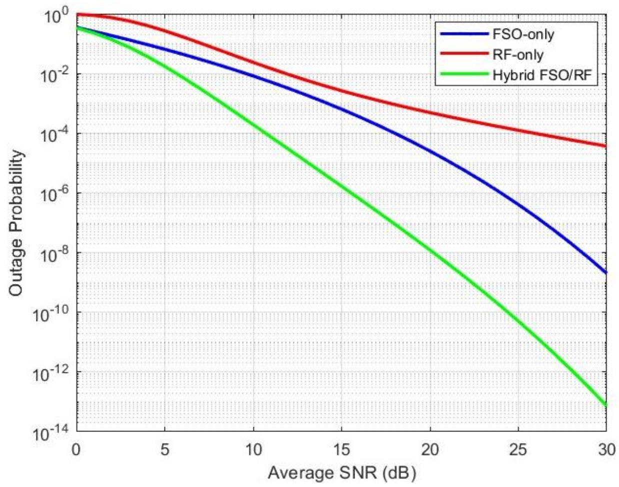


Figure 4. Outage probability for single-threshold FSO-only, RF-only and hybrid FSO/RF as a function of average SNR- γ_{th}^{FSO}=6 dB and γ_{th}^{RF}=3 dB

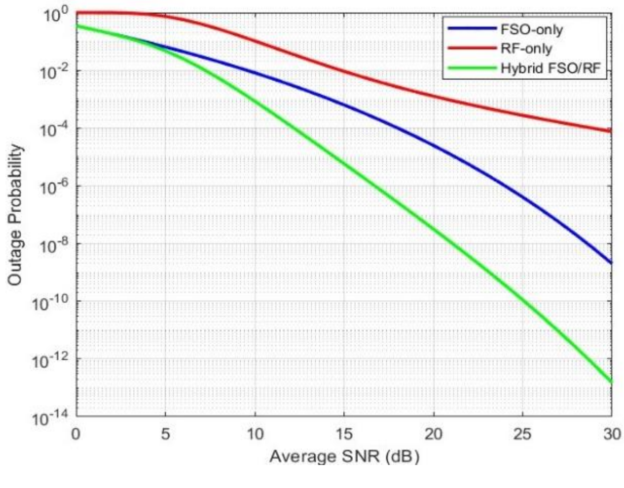
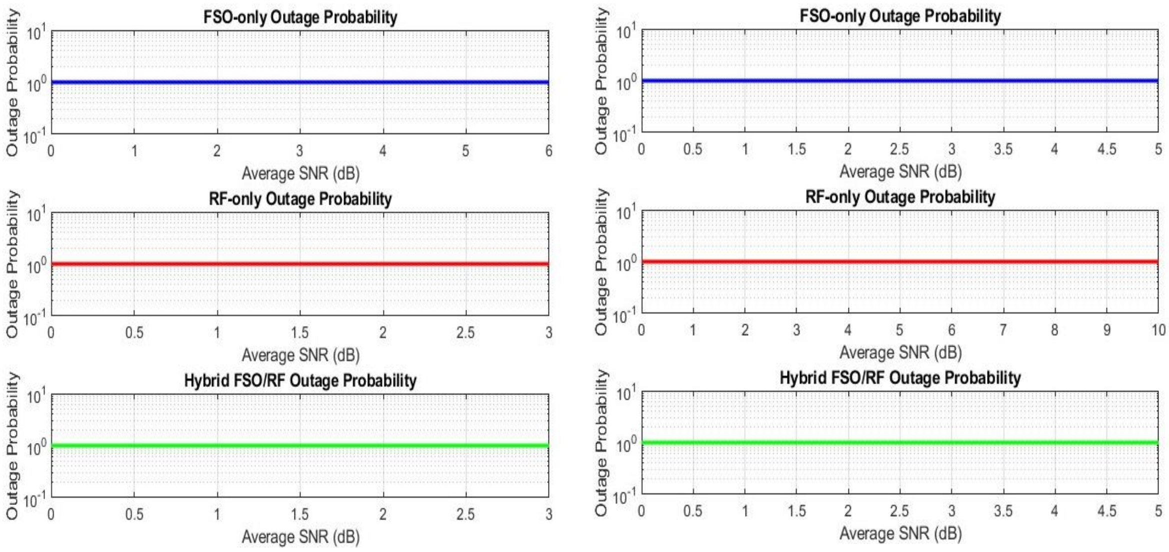


Figure 5. Outage probability for single-threshold FSO-only, RF-only and Hybrid FSO/RF as a function of average SNR- γ_{th}^{FSO}=γ_{th}^{RF}=6 dB

Figures 6 illustrates the operation of the proposed switching algorithm for the hybrid system at SNR- γ_{th}^{FSO}=6 dB and γ_{th}^{RF}=3 dB, and SNR- γ_{th}^{FSO}=5 dB and γ_{th}^{RF}=10 dB, respectively. It is observed that both links have different SNR thresholds. In Figure 6(a), the FSO link goes in outage at SNR below 6 dB while RF link goes in outage at SNR below 3 dB. Based on the hybridization and switching algorithm, the system only goes on outage when RF link goes on outage, because it has the lowest SNR threshold. Likewise in Figure 6(b), the FSO link goes on outage at SNR below 5 dB while RF link goes in outage at SNR below 10 dB. The hybrid system only goes on outage when FSO link goes on outage, because it has the lowest SNR threshold. This arrangement gives a clearer, more detailed perspective on how each system performs under the same conditions and particularly how the hybrid system potentially offers improved reliability over single-links system.



(a) (b)

Figure 6. Hybrid FSO/RF single-threshold switching operation at (a) SNR- γ_{th}^{FSO}=6 dB and γ_{th}^{RF} =3 dB and (b) SNR- γ_{th}^{FSO}=5 dB and γ_{th}^{RF}=10 dB

The analysis of the graphs depicting OP against received SNR highlights the significant advantages of the hybrid system utilizing single-threshold hard-switching mechanism. By effectively balancing the strengths of both links, the hybrid approach offers a reliable, low-outage solution for modern telecommunications networks, paving the way for more robust and efficient backhaul infrastructure. This study provides a clear pathway for deploying hybrid systems in real-world scenarios, addressing key industry challenges and contributing to the advancement of wireless communications technology.

The achieved results suggest that deploying hybrid FSO/RF systems in pico-macrocell backhauling can significantly enhance network reliability and performance. This is particularly important in urban and densely populated areas where environmental variability and interference are common challenges. The reduced OP implies improved service quality, fewer dropped connections, and enhanced user satisfaction. For network operators, the hybrid FSO/RF system presents an opportunity to deploy more resilient and cost-effective backhaul networks that can adapt to various environmental challenges. This is particularly beneficial for expanding network coverage in areas prone to weather changes or heavy RF interference.

4. CONCLUSION

In this study, we have evaluated the outage analysis of a single-threshold hard-switching hybrid FSO/RF system for reliable pico-macrocell backhauling applications. The FSO link is based on IM/DD and G-G distribution for the atmospheric turbulence. The backup RF link is based on Rician fading distribution. Also, we derived closed-form expressions for the PDF and CDF for the FSO and RF links respectively. The logic of the single-threshold hard-switching scheme ensures that the RF link backups the FSO link only under the conditions specified, reflecting a realistic and practical deployment scenario for the hybrid systems. Simulation results of the proposed scheme and evaluation of the outage of the links for RF-only, FSO-only and hybrid FSO/RF, presented significant improvements offered by the hybrid system as compared to standalone FSO-only or RF-only links. The findings of the study contribute to the advancement of hybrid backhaul technologies, providing a viable solution for the challenges faced in pico-macrocell backhauling.

ACKNOWLEDGEMENTS
We wish to acknowledge the African Union for the financial support. We are grateful to our families and friends for their love and encouragements.

REFERENCES
[1] M. A. Amirabadi and V. T. Vakili, "Performance analysis of a novel hybrid FSO/RF communication system," *IET Optoelectronics*, vol. 14, no. 2, pp. 66–74, Apr. 2020, doi: 10.1049/iet-opt.2018.5172.
[2] M. M. Ahamed and S. Faruque, "5G backhaul: requirements, challenges, and emerging technologies," *Broadband Communications Networks - Recent Advances and Lessons from Practice*, vol. 43, Sep. 2018, doi: 10.5772/intechopen.78615.
[3] H. Kaushal and G. Kaddoum, "Optical communication in space: challenges and mitigation techniques," *IEEE Communications Surveys & Tutorials*, vol. 19, no. 1, pp. 57–96, 2017, doi: 10.1109/COMST.2016.2603518.
[4] A. Mukhopadhyay and M. Ruffini, "Design methodology for wireless backhaul/fronthaul using free space optics and fibers," *Journal of Lightwave Technology*, vol. 41, no. 1, pp. 17–30, Jan. 2023, doi: 10.1109/JLT.2022.3210524.
[5] M. Y. Wani, H. Pathak, K. Kaur, and A. Kumar, "Free space optical communication system under different weather conditions," *Journal of Optical Communications*, vol. 44, no. 1, pp. 103–110, Jan. 2023, doi: 10.1515/joc-2019-0064.
[6] O. Aboelala, I. E. Lee, and G. C. Chung, "A survey of hybrid free space optics (FSO) communication networks to achieve 5G connectivity for backhauling," *Entropy*, vol. 24, no. 11, p. 1573, Oct. 2022, doi: 10.3390/e24111573.
[7] S. Magidi and A. Jabeena, "Free space optics, channel models and hybrid modulation schemes: a review," *Wireless Personal Communications*, vol. 119, no. 4, pp. 2951–2974, Aug. 2021, doi: 10.1007/s11277-021-08380-9.
[8] M. Z. Chowdhury, M. K. Hasan, M. Shahjalal, M. T. Hossan, and Y. M. Jang, "Optical wireless hybrid networks: trends, opportunities, challenges, and research directions," *IEEE Communications Surveys & Tutorials*, vol. 22, no. 2, pp. 930–966, 2020, doi: 10.1109/COMST.2020.2966855.
[9] P. K. Singya, B. Makki, A. D'Errico, and M. S. Alouini, "High-rate reliable communication using multi-hop and mesh THz/FSO networks," *IEEE Open Journal of the Communications Society*, vol. 5, pp. 3804–3823, Apr. 2024, doi: 10.1109/OJCOMS.2024.3413863.
[10] H. Kazemi, M. Uysal, and F. Touati, "Outage analysis of hybrid FSO/RF systems based on finite-state Markov chain modeling," in *2014 3rd International Workshop in Optical Wireless Communications (IWOW)*, Sep. 2014, pp. 11–15, doi: 10.1109/IWOW.2014.6950767.
[11] T. Rakia, H.-C. Yang, M.-S. Alouini, and F. Gebali, "Outage analysis of practical FSO/RF hybrid system with adaptive combining," *IEEE Communications Letters*, vol. 19, no. 8, pp. 1366–1369, Aug. 2015, doi: 10.1109/LCOMM.2015.2443771.
[12] S. K. Shrivastava, S. Sengar, and S. P. Singh, "A new switching scheme for hybrid FSO/RF communication in the presence of strong atmospheric turbulence," *Photonic Network Communications*, vol. 37, no. 1, pp. 53–62, Feb. 2019, doi: 10.1007/s11107-018-0792-6.
[13] W. M. R. Shakir, "Performance evaluation of a selection combining scheme for the hybrid FSO/RF system," *IEEE Photonics Journal*, vol. 10, no. 1, pp. 1–10, Feb. 2018, doi: 10.1109/JPHOT.2017.2771411.
[14] S. C. Tokgoz, S. Althunibat, and K. Qaraqe, "A link-selection mechanism for hybrid FSO-mmWave systems based on index modulation," *IEEE International Conference on Communications*, vol. 2020-June, 2020, doi: 10.1109/ICC40277.2020.9148634.
[15] Y. Wu, M. Jiang, G. Li, and D. Kong, "Systematic performance analysis of hybrid FSO/RF system over generalized fading channels with pointing errors," *Photonics*, vol. 9, no. 11, p. 873, Nov. 2022, doi: 10.3390/photonics9110873.
[16] J. Shao, Y. Liu, X. Du, and T. Xie, "Adaptive modulation scheme for soft-switching hybrid FSO/RF links based on machine learning," *Photonics*, vol. 11, no. 5, p. 404, Apr. 2024, doi: 10.3390/photonics11050404.
[17] J. Liang, M. Chen, and X. Ke, "Performance analysis of hybrid FSO/RF-THz relay communication system," *IEEE Photonics Journal*, pp. 1–10, 2024, doi: 10.1109/JPHOT.2024.3353194.
[18] M. Usman, H-C. Yang, and M.-S. Alouini, "Practical switching-based hybrid FSO/RF transmission and its performance analysis," *IEEE Photonics Journal*, vol. 6, no. 5, pp. 1–13, Oct. 2014, doi: 10.1109/JPHOT.2014.2352629.
[19] A. Touati, A. Abdaoui, F. Touati, M. Uysal, and A. Bouallegue, "On the effects of combined atmospheric fading and misalignment on the hybrid FSO/RF Transmission," *Journal of Optical Communications and Networking*, vol. 8, no. 10, p. 715, Oct. 2016, doi: 10.1364/JOCN.8.000715.
[20] S. Ghoname, H. A. Fayed, A. A. El Aziz, and M. H. Aly, "Performance evaluation of an adaptive hybrid FSO/RF communication system: impact of weather attenuation," *Iranian Journal of Science and Technology, Transactions of Electrical Engineering*, vol. 44, no. 1, pp. 119–128, Mar. 2020, doi: 10.1007/s40998-019-00244-0.
[21] H. Khalid, S. S. Muhammad, H. E. Nistazakis, and G. S. Tombras, "Performance analysis of hard-switching based hybrid FSO/RF system over turbulence channels," *Computation*, vol. 7, no. 2, p. 28, Jun. 2019, doi: 10.3390/computation7020028.
[22] N. Vishwakarma and R. Swaminathan, "Performance analysis of hybrid FSO/RF communication over generalized fading models," *Optics Communications*, vol. 487, p. 126796, May 2021, doi: 10.1016/j.optcom.2021.126796.
[23] S. Magidi and A. Jabeena, "Analysis of hybrid FSO/RF communication system under the effects of combined atmospheric fading and pointing errors," *Optical and Quantum Electronics*, vol. 54, no. 4, p. 210, Apr. 2022, doi: 10.1007/s11082-022-03586-y.
[24] N. Nikbakht-Sardari, M. Ghiamy, M. E. Akbari, and A. Charmin, "Novel adaptive hard-switching based hybrid RF-FSO system architecture using two threshold values in the presence of atmospheric turbulence and pointing error," *Results in Engineering*, vol. 17, p. 100813, Mar. 2023, doi: 10.1016/j.rineng.2022.100813.
[25] A. Y. u. Kassim, V. K. Oduol, and A. D. Usman, "Design and performance evaluation of a 350 m free space optical communications link for pico-macrocell backhauling," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 14, no. 3, pp. 2725–2736, Jun. 2024, doi: 10.11591/ijece.v14i3.pp2725-2736.
[26] P. Krishnan, "Performance analysis of hybrid RF/FSO system using BPSK-SIM and DPSK-SIM Over gamma-gamma turbulence channel with pointing errors for smart city applications," *IEEE Access*, vol. 6, pp. 75025–75032, 2018, doi: 10.1109/ACCESS.2018.2881379.

[27] V. S. Adamchik and O. I. Marichev, "Algorithm for calculating integrals of hypergeometric type functions and its realization in reduce system," in *ISSAC '90 Proceedings of International Symposium on Symbolic and Algebraic Computation*, 1990, pp. 212–224, doi: 10.1145/96877.96930.
[28] A. T. Pham, P. V. Trinh, V. V. Mai, N. T. Dang, and Cong-Thang Truong, "Hybrid free-space optics/millimeter-wave architecture for 5G cellular backhaul networks," in *2015 Opto-Electronics and Communications Conference (OECC)*, Jun. 2015, pp. 1–3, doi: 10.1109/OECC.2015.7340269.

BIOGRAPHIES OF AUTHORS

Abduljalal Yusha'u Kassim received a B.Eng. in Electrical Engineering and an M.Sc. in Telecommunications Engineering from Ahmadu Bello University, Zaria, Nigeria in 2015 and 2019 respectively. Currently, he is a lecturer in the Department of Electronics and Telecommunications Engineering at Ahmadu Bello University, Zaria, Nigeria since October 2018. In addition, he is a Ph.D. candidate at the Pan African University Institute for Basic Sciences, Technology, and Innovation (PAUSTI), Nairobi, Kenya. His research work mainly focuses on the design, simulation, and performance evaluation of hybrid FSO/RF Communications system for high-capacity backhauling in 5GB Networks. Engr. Abduljalal is a registered Engineer with the Council for the Regulation of Engineering in Nigeria (COREN) and a member of the International Association of Engineers (IAENG). He has won several scholarships, including the MTN Foundation scholarship for Science and Technology in 2012-2015 and the African Union Ph.D. Scholarship in 2022. He can be contacted at email: yushau.abduljalal@students.jkuat.ac.ke.

Vitalice Kalecha Oduol was granted a CIDA scholarship to pursue Electrical Engineering at McGill University in Montréal, Canada, where he obtained his B.Eng. (Hons.), M.Eng., and Ph.D. degrees in 1985, 1987, and 1992, respectively, in Electrical Engineering. While studying at McGill University, he worked as a research associate and teaching assistant. After completing his studies, he worked at MPB Technologies (Canada), INTELSAT in Washington DC, USA, and COMSAT Laboratories, USA. He returned to Kenya in 2003 and has been with the Department of Electrical and Information Engineering at the University of Nairobi. His research interests include the analysis, modeling, simulation, and evaluation of communication systems' performance. This encompasses signal processing, spectrum sensing in cognitive radio, emerging areas (5G and beyond), and the mitigation of rain attenuation in RF signals at high frequencies. Besides, he is interested in vehicle-to-vehicle (V2V) communications and vehicle-to-infrastructure (V2I) communications. He is a member of IEEE and was a two-time recipient of the Douglas Tutorial Scholarship at McGill University. He can be contacted at email: Vitalice.oduol@gmail.com.

Aliyu Danjuma Usman a professor of electronics and telecommunications engineering from Ahmadu Bello University, Zaria-Nigeria. Had his M.Eng. and Ph.D. from Electrical Engineering Departments of Bayero University Kano and Universiti Putra Malaysia in 2006 and 2011 respectively. Self-motivated personality with excellent skills in communications engineering and IT. Had over 25 years cognate working experience in tertiary educational institution. An independent researcher with a unique combination of detail-oriented mindset, driven personality, analytical skills, collaboration and proven ability of accomplishing several tasks. Published over 150 peer reviewed national and international journals/conferences and authored many books and book chapters. Currently, had over 450 Citations and 10 h-index. A recipient of a Patent and many research grants locally and internationally. Graduated many M.Sc. and Ph.D. students and many under his supervision. A visiting scholar, consultant and external examiner for many institutions within Nigeria and internationally. His research interest include; tele-traffic engineering, satellite communications, antenna radiation, wireless communications, microwave engineering. IoT, Terahertz frequencies, and 5G and beyond. He can be contacted at email: aliyuusman1@gmail.com.