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Performance evaluation of dual backhaul links RF/FSO for small cells of 5G cellular system

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ABSTRACT

Radio frequency (RF) backhaul links between the wireless stations especially between small cells stations such as relay stations (RSs) are insufficient with high capacities and huge number of users for 5G cellular networks. An alternative solution is using free space optics (FSO) communications, however, there are limitations in this system. In this paper we proposed a mixed of RF link together with FSO link. Using hard-selector between them and programmatically controlled according of quality of links to overcome the obstacles faced the transfer of high data. Based on the outage probability of each links an algorithm is proposed to select the optimal link and provide the power consumption with guaranteed high quality of the link. The analytical expressions for the outage probability and ergodic capacity are derived. The numerical results show the effectiveness of proposed model in terms of connectivity and capacity compared to other links.

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1. INTRODUCTION

One of the major problems that faced the fourth generation of cellular networks is that the weak coverage at the cell edge region of the first and second tier of central base station (eNB). The key to solve this issue using small cells such as relay stations (RSs) that deployed at the cell boundaries to increase the number of users with high efficiency [1]. Radio frequency (RF) backhaul links between the wireless stations especially between RSs are insufficient with high capacities and huge number of users for 5G cellular networks [1], [2]. Free space optics (FSO) introduced to provide a strong and reliable backhaul link for 5G mobile cellular networks [3], [4]. In addition, it ensures secure communications with a high throughput and high-speed data services due to laser's narrow beam and large unregulated spectrum. FSO systems easy to install and cost-effective that offers a strong immunity to interference [4], [5]. FSO systems have featured as successful solution for high data rate wireless transmission over short distances [3]. However, the increase in the number of users in the 5G need to provide high data throughput to keep pace with the development of cellular networks see in Figure 1.

Despite these advantages, FSO technology is obstructed by atmospheric turbulence-induced fading and pointing errors. These limitations shorten the FSO transmission to small distance [6], [7]. To increase the coverage and ensure the reliability of the FSO link for 5G cellular backhaul networks, RSs assisted the reduced from the frequent Interruption in wireless services at cell edge region [1]. The spectrum of FSO communication is an unlicensed spectrum, so it does not require a delegation from the government for the installation process compared to radio frequency (RF) transmission [3]. There are many types of encode techniques can be used for FSO systems to reduce atmospheric turbulences effect [8], [9]. However, both systems are featured by some specific virtues. A possible solution to improve the reliability of backhaul links between RSs is the integration of the FSO communication with a RF link system to form a mixed FSO/RF communication system as shown in Figure 2. This work investigates the performance of a mixed of multi-hop radio frequency backhaul link and free space optical link for 5G cellular networks. Furthermore, algorithm to select the optimal link for data transmission based on the outage probability and received signal was proposed in this work.

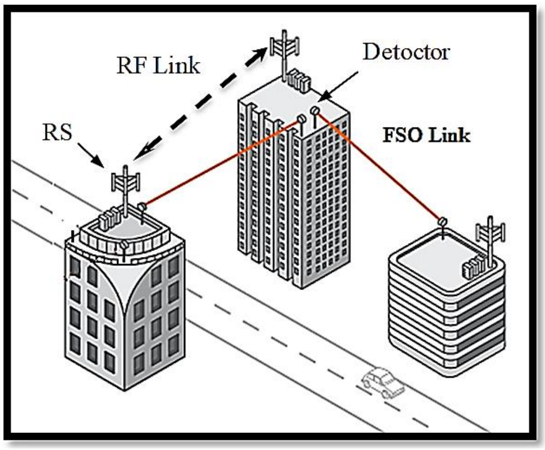

Figure 1. One of FSO backhaul link scenarios

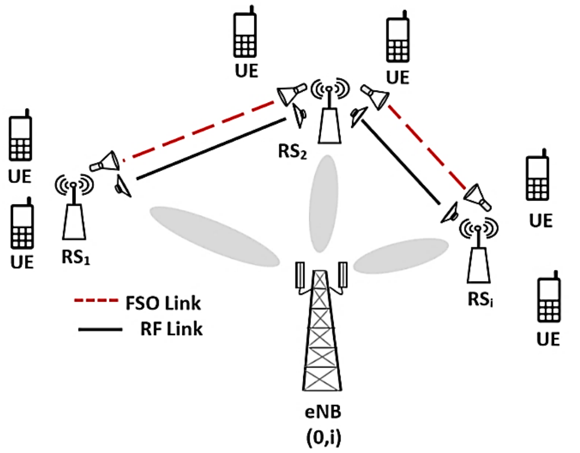

Figure 2. Proposed mixed RF/FSO of multi-hop relay station

2. RELATED WORK

For the last few years, mixed links have gained wide attention from researchers, aiming to improve the performance capacity. For example, Amirabadi and Vakili in [1] proposed a dual-hop of hybrid FSO/RF communication based on channel state information to connect users within the building to the BS. In research [5] mixed power of (PLC) and visible light communication (VLC) is proposed, was studied by practical manifestation. This hybrid approach is investigated based on the range, the connectivity and speed. The mix system of FSO and RF consider one of solutions aimed to increase the desire of high speed in wireless communication. Several study [10], [11] analyzed a hard-switching between FSO and RF link. The authors assumed that the FSO link follows Gamma-Gamma fading because of the effect of atmospheric turbulence. At each specific time, only one of the links will exploit. Various backhauling technologies have been considered such as optical fiber, FSO, RF, along with the hybrid combination of the FSO/RF in [12], where an iterative solution of two efficient methods to maximize the algebraic connectivity and resilience.

Aldhaibani and Al-Shareefi [13] proposed a new approach to increase the number of users and data rate and enhance the capacity by using two separate links: FSO and RF. These links applied to small cells at 5G cellular networks, FSO link superiority on the RF link in this work. Several research [14], [15] proposed a switching scheme for hybrid FSO and millimeter wave RF communications. The system is analyzed based on the outage probability and bit error rate (BER) [16]. The proposed system considered a scenario of with and without dual hop relaying of direct link. Using multiple-input multiple-output (MIMO) of RF and FSO to eavesdropper wiretaps the confidential information was studied in [14]. Authors depend on decoding the received signals from the source node and the channel state information (CSI) of the RF and FSO links. In the area of amplify and forward relay stations, several study [17], [18] studied the performance of an amplify and forward (AF) mixed RF-FSO relay over Nakagami-m and Gamma-Gamma fading channels. A closed-form for the outage probability and average of BER was derived in [17] and [18]. The performance of mixed FSO/RF multi-user relay system with aperture selection was studied in [15] based on opportunistic user scheduling in the presence of Poisson field interference. The main contributions of this work are increasing the number of user at the cell edge region by using the mixed RF/FSO link between the deployed RSs at the boundaries of cell. Moreover, we proposed an algorithm elects the best link provide high capacity based on the outage probability and received signal by users where the two links will combine to confront environmental conditions.

3. SYSTEM MODEL

The proposed model aims to provide the optimal backhaul link through selecting FSO, RF or hybrid RF/FSO links so as to satisfy data rate, connectivity, and reliability constraints. The multi-hop relay station mixed FSO/RF system of Figure 3 is considered. In proposed system model the main donor station eNB at the center of the cell and RSs is the relay station deployed at a certain position from eNB; i represents the number of RS and user equipment (UE) is the users attached with RS. Methodology of this paper divided by two categories, RF and FSO links, the derivation of the part RF link as follows:

The received signal through the direct link by the users is:

$$y_d(t) = \sqrt{P_t} h_d x(t) + n(t) \tag{1}$$

where $y_d(t)$ refers to received signal via the direct link. $\sqrt{P_t}$ is the transmitted power from eNB. h_d is the channel coefficient between eNB and RS, $n(t)$ is the additive white Gaussian noise (AWGN) at the destination [17], [19].

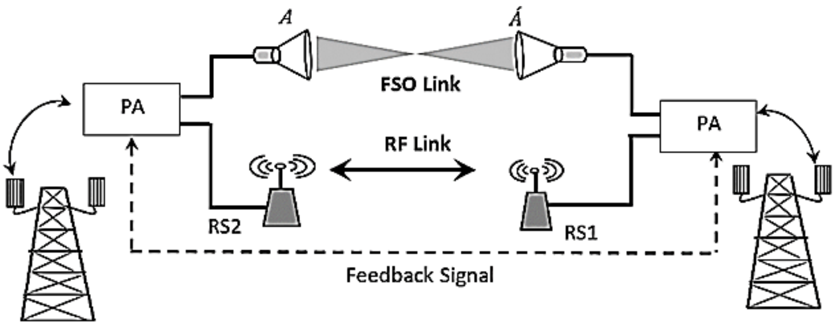

Figure 3. Proposed system model

Half-duplex mode is considered in this work to avoid self-interference [20], the time slots are divided between the transmission and reception in to two slots; time slot t_1 and time slot t_2 ,Therefore, the received RF signal at first time slot t_1 is:

$$y_{RS}(t_1) = \sqrt{P_t} h_{(0,i)}\, x(t_1) + \sqrt{P_{RS}} h_{(i,Nu)} x(t_2) + n(t) \tag{2}$$

where $h_{(0,i)}$ is the channel between eNB and i^{th} RS, $x(t)$ is the transmitted signal at any slot, $h_{(i,Nu)}$ is the channel between i^{th} RS, and Nu is the number of users attached with RS [17].

RS is the small cell placed as intermediate station between eNB and the users to increase the capacity for the users at cell boundaries, amplify and forward AF relay type of relay is used in this study, with amplification factor is ψ therefore the retransmitted signal form RS at the time slot t_1 and time slot t_2 can be write as (3):

$$x_{RS}(t_1) \ = \psi(\sqrt{P_t} h_{(0,i)} x(t_1) + \sqrt{P_{UE}} h_{(i,Nu)} x(t_2)) \ + n(t) \tag{3}$$

where, $\sqrt{P_{UE}}$ is the transmitted power by the user. Taking the expectation [17], [18] from the two sides we get (4):

$$E|x_{RN}(t_1)|^2 = E\left|\psi(\sqrt{P_t} h_{(0,i)} x(t_1) \ + \sqrt{P_{UE}} h_{(i,Nu)} x(t_2)) + n(t)\right|^2 \tag{4}$$

Axiomatically that $E|x(t)|^2 = P$ (the power of transmitted signal).

$$P_{RS} \ = \psi^2 \left|\sqrt{P_t} h_{(0,i)} x(t_1) \ + \sqrt{P_{UE}} h_{(i,Nu)} x(t_2) + n(t)\right|^2 \tag{5}$$

$$\psi = \sqrt{\frac{P_{RS}}{P_t \left|h_{(0,i)}\right|^2 + P_{UE} \left|h_{(i,Nu)}\right|^2 + n(t)}} \tag{6}$$

While the received signal by the user attached with RS is:

$$y_{UE}(t_2) = \psi\sqrt{P_t}h_{(0,i)}x_{RN}(t_1) + n(t) \quad (7)$$

Then,

$$y_{UE}(t_2) = \psi\sqrt{P_t}h_{(0,i)}\left(\psi\sqrt{P_t}h_{(0,i)}\right) + n(t) \quad (8)$$

Signal-to-noise ratio (SNR) at the users (end to end) via RF link can be expressed as:

$$snr = \frac{\psi^2 P_t |h_{(0,i)}|^2 |h_{(i,Nu)}|^2}{\left(\psi^2 |h_{(i,Nu)}|^2 + 1\right) n(t)}$$

The $x_{RS}(t_1)$ indicates the RF signal transmitted from the source RS. When the SIM scheme [10], [19] is employed in the relay, the retransmitted optical signal at the RS will be:

$$y_{opt}(t_2) = \psi(1 + \mu(y_{RS}(t_1)) \quad (9)$$

where the μ is the electrical to optical conversion coefficient, accordingly at the destination $\acute{A}$ (see the Figure 3) the received signal can be represented as:

$$y_{opt}(t_2) = K_0 I\{\psi(1 + \mu(y_{RS}(t_1))\} + n_1(t) \quad (10)$$

where the K_0 is the propagation constant and I represents irradiance fluctuations as a result of atmospheric turbulence induced fading [3], by filtering the CD component, the received signal at the destination can be re-write it as:

$$y_{opt}(t_2) = I\psi\mu(y_{RS}(t_1) + n_1(t) \quad (11)$$

By substation with (2) get:

$$y_{opt}(t_2) = I\left\{\psi(1 + \mu(\sqrt{P_t}h_{(0,i)}\,x(t_1) + \sqrt{P_{RS}}h_{(i,Nu)}x(t_2) + n(t))\right\} + n_1(t) \quad (12)$$

where $n_1(t)$ is an AWGN term with zero mean and variance $N_o/2$ [21]. Thus the SNR end to end of mixed links RF and FSO link can be depicted as [21]:

$$\gamma_{FSO} = \frac{I^2\mu^2\psi^2|h_{(0,i)}|^2 P_t}{I^2\mu^2\psi^2 N(t) + N_1(t)} \quad (13)$$

$$\gamma_{FSO} = \frac{\frac{|h_{(0,i)}|^2 P_t}{N(t)}\frac{I^2\mu^2}{N_1(t)}}{\frac{I^2\mu^2}{N_1(t)} + \frac{1}{\psi^2 N(t)}} \quad (14)$$

For simplification, let the $M = 1/\psi^2 N(t)$ and $\gamma_1 = |h_{(0,i)}|^2 P_t/N(t)$ and $\gamma_2 = I^2\mu^2/N_1(t)$, where the γ_1 represents the SNR of the first hop between the eNB to RS while the γ_2 represents the second hop between the RS and users via the FSO link only, therefore we can re-write the (14) as [12], [21]:

$$\gamma_{FSO} = \frac{\gamma_1\gamma_2}{\gamma_2 + M} \quad (15)$$

The SNR based on several factors, such as quality of service (QoS), distance between the sender and destination d, noise and interference. Simply, the channel coefficient can be defined as [13]: $|h|^2 = \eta(d)^{-a}$, where a is the path-loss exponent which is dependent on the environment, η is the transceivers' coefficients [22], [23].

The Rayleigh fading distribution with the probability density function (PDF) was assumed as a direct link between the eNB and RSs in this paper [24]. When the SNR falls below a specific threshold γ_{th} is defined an outage, the PDF of RF link is [15].

$$f_{\gamma 1}(\gamma_1) = \frac{1}{\gamma_{th,RF}} e^{-\gamma_1/\gamma_{th,RF}} \tag{16}$$

where the $\gamma_{th,RF}$ is the threshold of SNR for RF link. According to [19] we can estimate the outage probability using the cumulative distribution function (CDF) of the RF link by integrating (16) to get:

$$\mathrm{P}_{out}^{RF} = \int_0^{\gamma_{th,RF}} f_{\gamma 1}(\gamma_1) = 1 - e^{-\gamma_1/\gamma_{th,RF}} \tag{17}$$

While the link between the RS and the users of FSO is assumed to experience the gamma-gamma fading distribution with the PDF given in [10], [19] as the (18)

$$f_{\gamma 2}(\gamma_2) = \frac{(\alpha\beta)^{(\alpha+\beta)/2} \gamma_2^{(\alpha+\beta)/4}}{\Gamma(\alpha)\Gamma(\beta)\overline{\gamma}_2^{(\alpha+\beta)/4}} K_{(\alpha-\beta)}\left(2\sqrt{\alpha\beta\sqrt{\frac{\gamma_2}{\overline{\gamma_2}}}}\right) \tag{18}$$

where the $\overline{\gamma_2}$ is the average of SNR of FSO link and the $K_{(a)}(0)$ is the Bessel function of the second kind of order a, and the α, β is the atmospheric turbulence of FSO link conditions which are defined in (5) and (6) of [10], [21], [25], and as in (19) and (20).

$$\alpha \cong exp\left[\frac{0.49\sigma_R^2}{(1+0.11\sigma_R^{\frac{12}{5}})^{7/6}}\right] - 1 \tag{19}$$

$$\beta \cong exp\left[\frac{0.51\sigma_R^2}{(1+0.69\sigma_R^{\frac{12}{5}})^{7/6}}\right] - 1 \tag{20}$$

where σ_R^2 is Rytov variance as mentioned in (21) and defined in (7) of [20]:

$$\sigma_R^2 = 1.23(\frac{2\pi}{\lambda})^{7/8} C_n^2 \mathcal{L}^{11/6} \tag{21}$$

where C_n^2 is the altitude-dependent turbulence strength and changing from $10^{-17}$to 10^{-13} $\mathrm{m}^{-2/3}$ based on the atmospheric turbulence conditions, $\mathcal{L}$ is the length of the optical link [19].

CDF for the Gamma-Gamma FSO link according to (18) and [10], [19] can be re-written as (22):

$$\mathrm{P}_{out}^{FSO} = \frac{(\alpha\beta)^{(\alpha+\beta)/2} \gamma_2^{(\alpha+\beta)/4}}{\Gamma(\alpha)\Gamma(\beta)\overline{\gamma}_2^{(\alpha+\beta)/4}} G_{1,3}^{2,1}\left(\alpha\beta\sqrt{\frac{\gamma_2}{\overline{\gamma_2}}}\middle|_{\frac{\alpha-\beta}{2}, \frac{\beta-\alpha}{2}, \frac{\alpha+\beta}{2}}^{1-\frac{\alpha/\beta}{2}}\right) \tag{22}$$

where the $G_{p,q}^{m,n}$[.] is the Meijer G-function as mentioned by [10], [19], [24]. Now, for the total outage probability of both links (RF&FSO) by using (17) and (22) can be expressed as (23).

$$\mathrm{P}_{out}^{RF/FSO} = \frac{(\alpha\beta)^{(\alpha+\beta)/2} \gamma_2^{(\alpha+\beta)/4}}{\Gamma(\alpha)\Gamma(\beta)\overline{\gamma}_2^{(\alpha+\beta)/4}} G_{1,3}^{2,1}\left(\alpha\beta\sqrt{\frac{\gamma_2}{\overline{\gamma_2}}}\middle|_{\frac{\alpha-\beta}{2}, \frac{\beta-\alpha}{2}, \frac{\alpha+\beta}{2}}^{1-\frac{\alpha/\beta}{2}}\right)\left(1 - e^{-\gamma_1/\gamma_{th,RF}}\right) \tag{23}$$

The channel capacity of the mixed RF/FSO link can be calculated in relation of the capacity of individual FSO and RF links as [25], [26].

$$\bar{\mathcal{R}} = R^{FSO}(\bar{\gamma}_2) + \mathrm{P}_{out}^{FSO}(\bar{\gamma}_2) R^{RF}(\gamma_{th,RF}) \tag{24}$$

where $\mathrm{P}_{out}^{FSO}(\bar{\gamma}_2)$ is given by (22), $R^{FSO}(\bar{\gamma}_2)$ and $R^{RF}(\gamma_{th,RF})$ are the channel capacity of FSO and RF links, respectively. When they are active, and after referencing the (16) and (18) are given by (25) and (26)

$$R^{FSO}(\bar{\gamma}_2) = \int_{\gamma_{th}}^{\infty} BW^{FSO} \cdot log_2(1+\gamma) f_{\gamma 2}(\gamma_2) d\gamma \tag{25}$$

$$R^{RF}\left(\gamma_{th,RF}\right) = \int_{\gamma_{th}}^{\infty} BW^{RF} \cdot log_2(1+\gamma) f_{\gamma 1}(\gamma_1) d\gamma \tag{26}$$

where, the BW^{FSO} BW^{FSO} are the bandwidths of the FSO and RF links respectively.

$$\mathcal{R}(\gamma_{th}) = \int_{\gamma_{th}}^{\infty} log_2(1+\gamma) \tag{27}$$

4. PROPOSED ALGORITHM SELECTION

In this section an algorithm to select of optimal link is proposed, this algorithm based on the evaluation the end-to-end link for the SNR and outage probability for both RF and FSO, according to (17), (22) and (23). There are three cases RF, FSO and RF/FSO are considered in this algorithm. The proposed algorithm (PA) finds a solution to the optimization problem starting with RF link considering other links to be selected. If the selected RF link does not provide the required of outage level, RF link can be replaced by FSO or mixed RF/FSO. The optimal link will be elected for data exchange between the RSs to eliminate interruption in wireless services at the cell edge region and provide the reliable connection between RSs the as demonstrated in Figure 4.

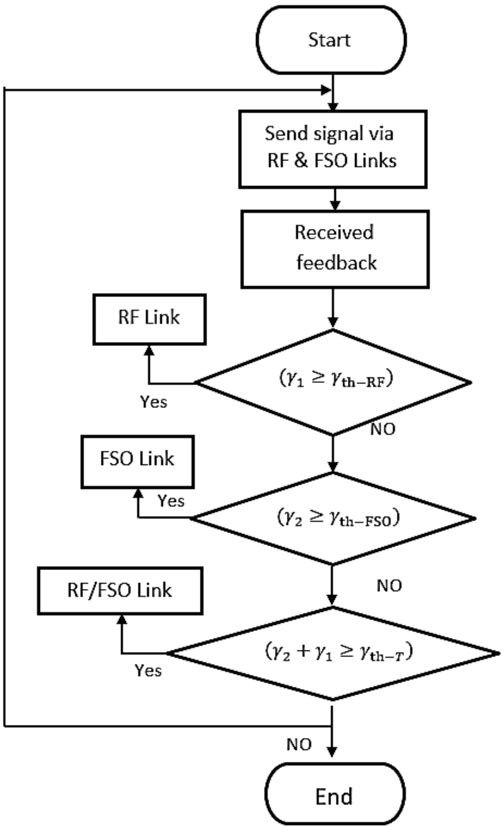

Figure 4. Proposed algorithm to select optimal link

5. RESULTS AND DISCUSSION

To explain the analysis, some arithmetical examples were presented. The transmitted power is assumed to be equal to 320 mW for FSO link and 16 mW for RF [10]. As given in [10], We have used typical values for strong atmospheric turbulence conditions (β=1.342, and α = 2.064). We selected typical values (α=2.064, β=1.342) for Gamma-Gamma distribution for strong atmospheric turbulence [11], [25]. The simulation parameters of proposed system are chosen from [20].

In Figure 5, according to (17) and (22), the outage probability offered for four different cases as a function of the average end to end SNR for the FSO only link denoted by the blue curve. Also, the green curve shows the outage probability for RF-only case that means the RF link continue to be inefficient for SNR values compared with FSO link.

The red and black curves are for FSO-only where the outage probability as a function of outage threshold for different values of $\gamma_{th,RF}$. Here we assume a strong atmospheric turbulence of FSO link with an average FSO link SNR $\gamma_{th,RF}$=5 dB and $\gamma_{th,RF}$=10. Figure 5 shows that mixed FSO/RF system overcomes the other case in respect to reliability. In addition, by increasing the average SNR for the RF, the reliability in the mixed system improves which means that the performance is improved for larger SNR values of the RF link.

The PA introduced the solutions for optimization problem as shown in Figure 6. This algorithm allows to aggregate the two links RF and FSO if each link separately did not provide the requirement for high data rate transmission. Figure 6 shows that hybrid FSO/RF system overcomes the other case in respect to reliability. Moreover, it is observed that for a hybrid system, by increasing the average SNR PA, the reliability is also improved. It saves energy consumption and overcome on the rain and snow attenuation on FSO and shadowing in RF by select the optimal link based on quality of service (QoS).

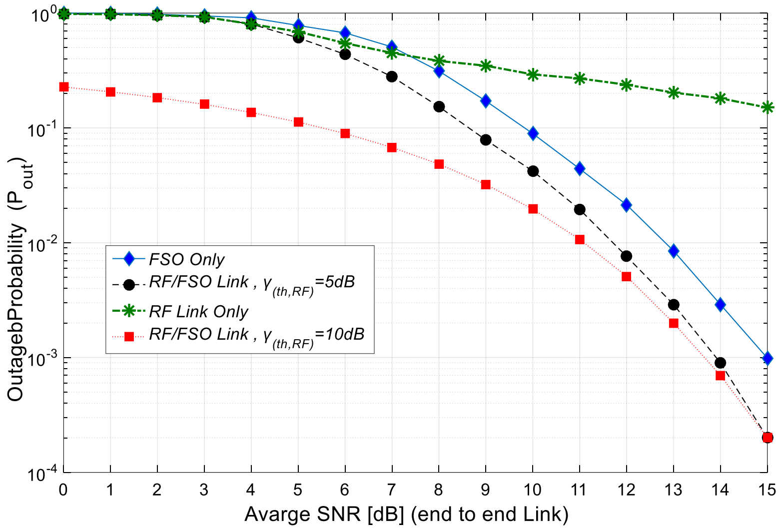

Figure 5. Outage probability with the end-to-end average SNR

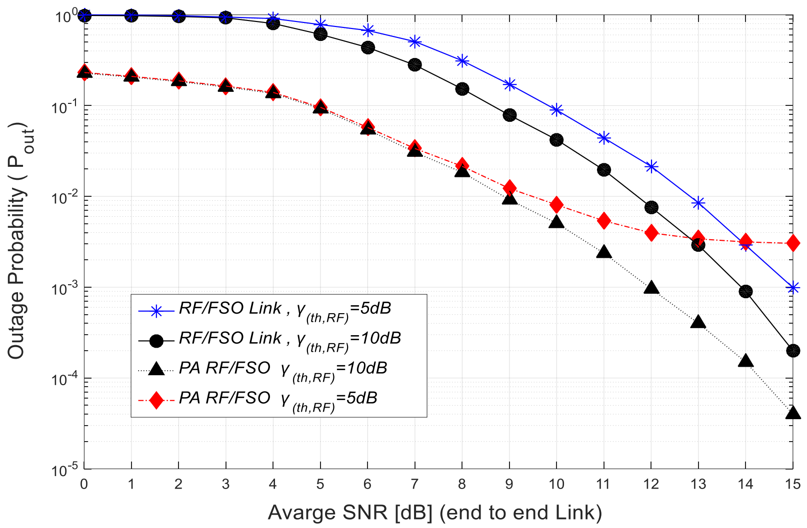

Figure 6. Probability as a function of end-to-end average SNR using PA

Figure 7 demonstrates the comparison between proposed system for consideration the mixed RF/FSO and FSO system that presented by [13] in terms of received signal relative to the distance between the transmitter and the receiver. The proposed distance between the two RSs is 600 m, so, from Figure 6, we observed that proposed system using PA outperform the results of [13] by 35% and 60% for threshold SNR of 5 and 10 respectively. Moreover, this enhancement increases by increasing the distance because the proposed system facing on the fading in received signal due to the long range between the sender and receiver by aggregates the RF and FSO links.

Figure 8 shows three curves of capacities of FSO-only, mixed system of RF/FSO with SNR $\gamma_{th,RF}$= 5 dB and $\gamma_{th,RF}$ =10 dB according to (24), (25) and (26), The results prove there are improvements in the capacity by using mixed FSO/RF system. For example, at the SNR 6dB enhancement in capacity from 1 bps/Hz to 1.7 bps/Hz and to 3.3 bps/Hz with $\gamma_{th,RF}$= 5 dB and $\gamma_{th,RF}$=10 dB respectively. The proposed system provides a high benefit to overcome frequent interruption at cell edge due to low SNR, where the improvements are rising when the low SNR with the mixed RF/FSO. For example, at SNR=1 the capacity increases from 0.2 dB to 1.1dB and 3 dB as shown in Figure 8.

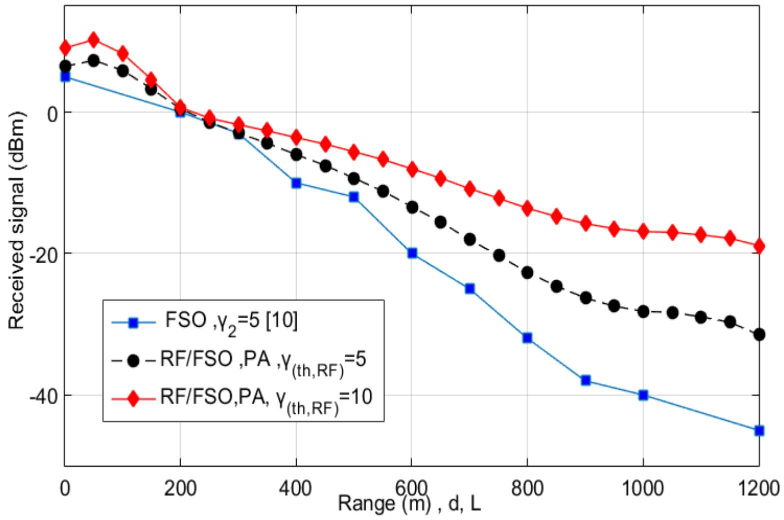

Figure 7. The comparison of received signal for proposed model and presented work by [10] over different distances

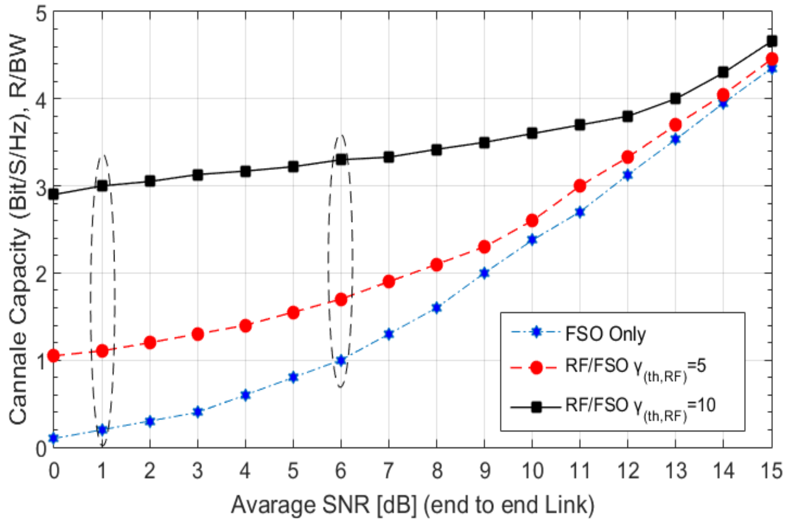

Figure 8. Channel capacity versus average SNR end to end of FSO link

6. CONCLUSION

In this paper, we have presented a new model to enhance the backhaul links between multi-hop relays which deployed at cell edge region in 5G cellular networks. This link composed of RF and FSO links together to overcome interference, fading and environmental constraints. Based on analytical expressions of the outage probability and ergodic capacity an algorithm has been proposed to programmatically control and select the optimal link from to RF, FSO or mixed RF/FSO. This efficient model provided a lower consumption of power with warranty high quality of link. Numerical results indicated that mixed RF/FSO backhaul link exceled other links under different turbulence conditions. In addition, the mixed RF/FSO fulfilled best performance and important enhancement in terms of reliability and conductivity as compared to RF or FSO individually.

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