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Reconfigurable Intelligent Surface Assisted Full-Duplex Relay Hybrid FSO/RF Systems over Atmospheric Turbulence with Foggy Impairments

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ABSTRACT: The outage probability performance of a hybrid free space optical (FSO)/radio frequency (RF) system with a reconfigurable intelligent surface (RIS) assisted full-duplex relay is presented in this paper. The FSO link follows the Gamma-Gamma distribution over pointing error and atmospheric turbulence with random foggy impairments. The RF link between the relay and the destination is subject to Nakagami-m distributions, while the RIS links and relay self-interference (SI) link follow Rayleigh fading. As a result, the RIS-to-relay link's cumulative distribution function (CDF) of the signal to interference plus noise ratio (SINR) is obtained. On the basis of this, the system's outage probability is determined according to the decode and forward relay protocol. Thus, Monte-Carlo simulations are utilized to verify the obtained expression's accuracy. Our findings show how atmospheric turbulence, pointing errors, fog conditions, and the number of RIS reflecting elements affect the system performance. Furthermore, it is concluded that, under the identical channel conditions, heterodyne detection performs better than intensity modulation/direct detection (IM/DD).

1. INTRODUCTION

Reconfigurable intelligent surface (RIS) has been considered as a potential option in wireless communication systems to avoid signal transmission obstruction and/or enhance the received signal-to-noise ratio (SNR) by offering an alternate wireless propagation channel [1]. The RIS consists of a passive number of reflecting elements in which each is capable of steering the impinging wave towards the desired direction compared to conventional technologies [2]. It is an energy-efficient and low-cost device that requires no active RF chains for transmission. Thus, it has been established that, with certain number of reflecting elements in RIS, it offers better performance than the decode-and-forward relay node [3]. The RIS-assisted systems have been widely studied in open literature, specifically to enhance the performance of other transmission link for better reliability [4].

In view of recent attentions, hybrid FSO/RF transmission has been suggested in literature as a prospective technology to improve the performance of FSO systems. It is observed that FSO link is highly susceptible to atmospheric turbulence (AT), pointing error (PE), and weather conditions such as fog and snow [5]. However, AT, PE, fog, and snow have no impact on the RF propagation except heavy rain and multipath fading. As a result, a hybrid paradigm which combines the benefits of both RF technology and FSO is a good candidate for providing a reliable high data rate wireless system where the RF link serves as a backup. In this case, the performance of hybrid FSO/RF links has been studied in different works, specifically, in [6] where the performance of diversity combiner technique was studied on hybrid FSO/RF systems. The authors in [7] studied the performance of underlay cognitive radio-based hybrid FSO/RF systems with respect to physical layer security. A practical switching-based hybrid FSO/RF system was presented in [8], and the authors in [9] studied the performance a hybrid FSO/RF system under generalized fading model. A practical approach to increase the utilization of FSO channel in hybrid FSO/RF system was depicted in [10]. However, all these studied were based on single hop transmission. Under the dual-up transmission, a hybrid FSO/RF system comprising a decode-and-forward (DF) relaying-based FSO and RF sub-system was presented in [11] where sub-systems employ maximum ratio combiner to combine the data at the destination. In addition, the hybrid FSO/terahertz-based backhaul network was studied in [12] to provide high-data rate reliable communication to the terrestrial mobile users at millimeter wave bands. Moreover, a multi-hop parallel hybrid FSO/RF cooperative system was presented in [13]. Also, a space-air-ground integrated network-based dual-hop system model for uplink satellite communication with hybrid FSO/RF links was presented in [14] and the performance was investigated.

Relay-assisted communication is a potential technology to combat the channel impairments issues in wireless systems. The concept is based on the use of a single or many relay nodes to aid the data transmission between the source and the destination. The RIS-assisted hybrid FSO/RF system has been presented in [15] where the RIS was employed to aid the RF link against transmission blockage. However, the proposed system was not a relay-assisted communication. Also, the authors in [16] studied the performance of an RIS-aided cooperative

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hybrid FSO/RF network, but the relay mode was based on half duplex where the self-interference at the relay was negligible. Also, the foggy condition was not considered as channel impairments on the FSO link. Motivated by these observations, an RIS-assisted full duplex relay hybrid RF/FSO system is presented in this paper. The joint effect of AT, PE, and fog is considered as channel impairments on the FSO link. Thus, the CDF of the SINR of the RIS-to-Relay is derived. Through this, the system outage probability is obtained based on DF relay protocol.

The structure of this paper is as follows. The channel and system models are shown in Section 2. We discuss the proposed system's outage performance analysis in Section 3. Section 4 presents the discussions of the outcomes for the proposed system. Section 5 gives the conclusion remarks.

2. SYSTEM AND CHANNEL MODELS

A dual-up RIS with N reflecting elements assisted full duplex relay communication system is presented in Figure 1 where RIS aids the transmission of source information due to blockage between the source and the relay node. The hybrid FSO/RF links are then deployed to convey the source information to the destination for which the system can benefit from both the technologies. In this case, the FSO link is assumed to follow the Gamma-Gamma distribution over pointing error and atmospheric turbulence with random foggy impairments. The RF link between the relay and the destination is subject to Nakagami-m distributions, while the RIS links and relay self-interference (SI) link are subjected to Rayleigh distribution fading. Owing to fading and blockages, there is no direct link between the source and destination. Also, it is assumed that the FSO link is the primary link due to its capability to offer high data-rate secured transmission. The relay node is subject to full-duplex decode-and-forward (DF) protocol. At the destination, the best link with the highest SNR is selected with the aid of selection combiner technique.

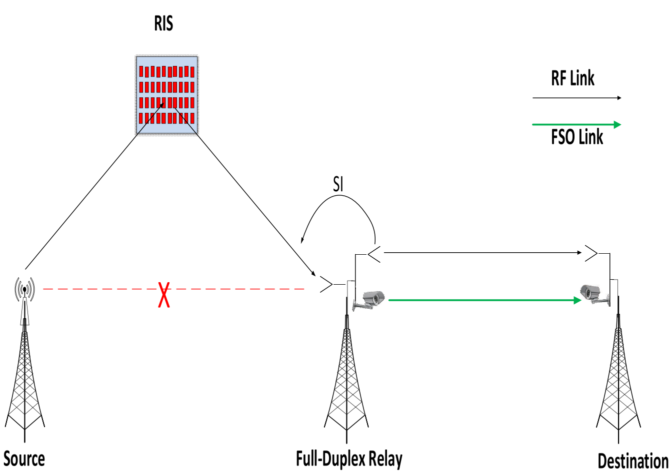

FIGURE 1. RIS assisted full duplex relay hybrid FSO/RF system model.

In this study, the instantaneous SNR of the RIS link is a non-central chi-square random variable with one degree of freedom, and it is assumed that the links follow Rayleigh distribution. Thus, the probability density function (PDF) of the SNR γ_{RIS} can thus be written as [17, 18]:

$$f_{\gamma_{RIS}}(\gamma) = \frac{\pi\sqrt{2}}{2\mu}\exp\left(-\frac{\Psi}{2\mu^2}\right)\sum_{k=0}^{\infty}\frac{(-1)^k}{k!\,(2\mu^2)^k}\gamma^{k-1/8} G_{1,3}^{1,0}\left(\frac{\Psi}{4\eta^4}\gamma\middle|\begin{matrix}1/2\\0,\ 1/2,\ 1/2\end{matrix}\right) \tag{1}$$

where $\mu^2 = N\bar{\gamma}_{RIS}\left(1-\frac{\pi^2}{16}\right)^2$ and $\Psi = \bar{\gamma}_{RIS}\left(\frac{\pi}{4}N\right)^2$ with $\bar{\gamma}_{RIS}$ signifies the average SNR of the source-RIS-relay link. Moreover, the CDF of the RIS link is provided as:

$$F_{\gamma_{RIS}}(\gamma) = \sum_{k=0}^{\infty}\frac{\exp(-\Psi/2\mu^2)}{k!\Gamma(k+1/2)}\left(\frac{\Psi}{2\mu^2}\right)^k G_{1,2}^{1,1}\left(\frac{\gamma}{2\mu^2}\middle|\begin{matrix}1\\k+1/2,\ 0\end{matrix}\right) \tag{2}$$

Additionally, the RF link between the relay and the destination can be described by Nakagami-m distribution, and the PDF of the link can be specified as:

$$f_{\gamma_{RF}}(\gamma) = \frac{\lambda^m}{\Gamma(m)}\gamma^{m-1}\exp(-\lambda\gamma) \tag{3}$$

where $\lambda = m/\bar{\gamma}_{RF}$ and $\bar{\gamma}_{RF}$ is the average SNR of the RF link. The CDF of the RF link can be written as:

$$F_{\gamma_{RF}}(\gamma) = \frac{\Upsilon(m,\lambda\gamma)}{\Gamma(m)} = 1-\sum_{n=0}^{m-1}\frac{\lambda^n}{k!}\gamma^n xp(-\lambda\gamma) \tag{4}$$

The self-interference at the relay node is impacted by Rayleigh fading distributions, hence, the PDF of the self-interference is defined as:

$$f_{\gamma}(\gamma) = \Omega\exp(-\Omega\gamma) \tag{5}$$

where $\Omega = 1/\bar{\gamma}_{SI}$ with $\bar{\gamma}_{SI}$ denoting the average SNR of the SI link. On the other hand, the CDF of the SI link can be given as:

$$F_{\gamma}(\gamma) = 1-\exp(-\Omega\gamma) \tag{6}$$

The FSO link is assumed to undergo atmospheric turbulence, pointing error and fog. Therefore, the atmospheric turbulence is characterized by Gamma-Gamma distributions, and the combine effect the channel impairments is assumed to follow probabilistic model with the PDF defined as [19]:

$$f_{\gamma_{FSO}}(\gamma) = \frac{\eta\omega^k}{r\bar{\gamma}_f^{1/r}\gamma^{1-1/r}} G_{1+k,\,3+k}^{3+k,\,0}\left(\Phi\left(\frac{\gamma}{\bar{\gamma}_f}\right)^{1/r}\middle|\begin{matrix}\xi^2,\ \{\omega\}_1^k\\ \xi^2-1,\alpha-1,\beta-1,\{\omega-1\}_1^k\end{matrix}\right) \tag{7}$$

where $\eta = \frac{\alpha\beta\xi^2}{A_o\Gamma(\alpha)\Gamma(\beta)}$, $\Phi = \frac{\alpha\beta}{A_o}$, with ξ signifying the pointing error; α and β are the scintillation parameters which are specified in [20]; k represents the fog shape parameter; $\omega =$

$4.343/d\beta^{fog}$ with d denoting the distance between the relay and destination; and β^{fog} indicates the fog scale parameter. The notation $\{x_i\}_1^v = \{x_1, ..., x_v\}$. The CDF of the FSO link can be determined by integrating (7) using the identity defined in [21] as:

$$F_{\gamma_{FSO}}(\gamma) = \frac{\eta\omega^k}{\bar{\gamma}_f^{1/r}} \gamma^{1/r} G_{2+k,\,4+k}^{3+k,\,1} \left(\Phi \left(\frac{\gamma}{\bar{\gamma}_f} \right)^{1/r} \middle| \begin{matrix} 0,\, \xi^2,\, \{\omega\}_1^k \\ \xi^2-1, \alpha-1, \beta-1, \{\omega-1\}_1^k \end{matrix} \right) \quad (8)$$

3. PERFORMANCE ANALYSIS

Outage probability is one of the performance metrics to characterize the effect of channel impairment on wireless systems. Thus, it describes the probability SNR falls below a threshold value γ_{th}. Mathematically, the exact outage probability can be written as [22]:

$$P_{out}(\gamma_{th}) = F_{eq}(\gamma_{th}) \quad (9)$$

The FSO and RF link are independent, hence the outage probability of the hybrid link can be provided as [8]:

$$P_{out}^{Hyd}(\gamma_{th}) = F_{\gamma_{FSO}}(\gamma_{th}) \times F_{\gamma_{RF}}(\gamma_{th}) \quad (10)$$

Thus, invoking (4) and (8) into (10), the outage probability of the hybrid link can be expressed as:

$$P_{out}^{Hyd}(\gamma_{th}) = \psi\gamma^{\frac{1}{r}} G_{2+k,\,4+k}^{3+k,\,1} \left(\Phi \left(\frac{\gamma}{\bar{\gamma}_f} \right)^{\frac{1}{r}} \middle| \begin{matrix} 0,\, \xi^2,\, \{\omega\}_1^k \\ \xi^2-1, \alpha-1, \beta-1, \{\omega-1\}_1^k \end{matrix} \right) \Upsilon(m, \lambda\gamma) \quad (11)$$

where $\psi = \eta\omega^k/\Gamma(m)\bar{\gamma}_f^{\frac{1}{r}}$.

Since the system utilizes DF relay protocol, the equivalent end-to-end (E2E) outage probability for the concern system can be defined as [12]:

$$P_{out}^{E2E}(\gamma_{th}) = F_{RIS,SINR}(\gamma_{th}) + F_{\gamma}^{Hyd}(\gamma_{th}) - F_{RIS,SINR}(\gamma_{th}) F_{\gamma}^{Hyd}(\gamma_{th}) \quad (12)$$

where $F_{RIS,SINR}(\gamma_{th})$ is the CDF of signal to interference plus noise ratio (SINR) of the RIS-to-relay link, and $F_{\gamma}^{Hyd}(\gamma_{th})$ is the CDF of the hybrid link.

$F_{RIS,SINR}(\gamma_{th})$ can be expressed as [23]:

$$F_{RIS,SINR}(\gamma) = \left(\frac{\gamma_{SR}}{\gamma_{RR}+1} \right) \triangleq \int_0^\infty F_{RIS,R}\left[\gamma(\gamma_{RR}+1)\right] f_{RR}(\gamma_{RR})\, d\gamma_{RR} \quad (13)$$

Therefore, by putting (2) and (5) into (13), $F_{RIS,SINR}(\gamma)$ can be expressed as:

$$F_{RIS,SINR}(\gamma) = \Omega\Delta_{RIS} G_{1,2}^{1,1} \int_0^\infty \left(\frac{(\gamma_{RR}+1)}{2\mu^2}\gamma \middle| \begin{matrix} 1 \\ k+1/2,\, 0 \end{matrix} \right) \exp(-\Omega\gamma_{RR})\, d\gamma_{RR} \quad (14)$$

where $\Delta_{RIS} = \sum_{k=0}^{\infty} \frac{\exp(-\Psi/2\mu^2)}{k!\Gamma(k+1/2)} \left(\frac{\Psi}{2\mu^2}\right)^k$.

By letting $\gamma_{RR} + 1 = Z$, $\gamma_{RR} = Z - 1$, and $d\gamma_{RR} = dZ$, (14) can further be expressed as:

$$F_{RIS,SINR}(\gamma) = \Omega\Delta_{RIS} \exp(\Omega) \int_0^\infty \exp(-\Omega Z)\, G_{1,2}^{1,1} \left(\frac{\gamma}{2\mu^2} Z \middle| \begin{matrix} 1 \\ k+1/2,\, 0 \end{matrix} \right) dZ \quad (15)$$

By applying the integral identity stated in [21, Eq. (3.325.2)], (15) can be solved as:

$$F_{RIS,SINR}(\gamma) = \Omega\Delta_{RIS} \exp(\Omega)\, G_{2,2}^{1,2} \left(\frac{\gamma}{2\mu^2\Omega} \middle| \begin{matrix} 0,\, 1 \\ k+1/2,\, 0 \end{matrix} \right) \quad (16)$$

Then, substituting (11) and (16) into (12), the system equivalent E2E outage probability can be evaluated in closed-form as:

$$\begin{aligned} P_{out}^{E2E}(\gamma_{th}) &= \Omega\Delta_{RIS} \exp(\Omega)\, G_{2,2}^{1,2} \left(\frac{\gamma}{2\mu^2\Omega} \middle| \begin{matrix} 0,\, 1 \\ k+1/2,\, 0 \end{matrix} \right) \\ &+ \psi\gamma^{\frac{1}{r}} G_{2+k,4+k}^{3+k,1} \left(\Phi\left(\frac{\gamma}{\bar{\gamma}_f}\right)^{\frac{1}{r}} \middle| \begin{matrix} 0, \xi^2, \{\omega\}_1^k \\ \xi^2-1, \alpha-1, \beta-1, \{\omega-1\}_1^k \end{matrix} \right) \Upsilon(m, \lambda\gamma) \\ &- \Omega\Delta_{RIS}\psi\gamma^{\frac{1}{r}} \exp(\Omega)\, G_{2,2}^{1,2} \left(\frac{\gamma}{2\mu^2\Omega} \middle| \begin{matrix} 0, 1 \\ k+\frac{1}{2}, 0 \end{matrix} \right) \times G_{2+k,4+k}^{3+k,1} \left(\Phi\left(\frac{\gamma}{\bar{\gamma}_f}\right)^{\frac{1}{r}} \middle| \begin{matrix} 0, \xi^2, \{\omega\}_1^k \\ \xi^2-1, \alpha-1, \beta-1, \{\omega-1\}_1^k \end{matrix} \right) \Upsilon(m, \lambda\gamma) \end{aligned} \quad (17)$$

4. NUMERICAL RESULTS AND DISCUSSION

In this section, the performance of a dual-up RIS assisted full-duplex relay hybrid FSO/RF system is presented. The system outage probability is derived under the AT, PE, and random fog conditions. Through the use of Monte-Carlo simulations, the derived expression's correctness is confirmed. The following settings are made for the simulation of the results, unless otherwise specified: $N = 5$, $m = 2$, $\xi = 6.5$, $\gamma_{th} = 5$ dB,

$d = 0.2\,\text{km}$, $\bar{\gamma}_{SI} = 5\,\text{dB}$, $\bar{\gamma}_{RIS} = 2\,\text{dB}$. The channel condition is under the light fog ($\beta^{fog} = 12.06$, $k = 2$) and moderate fog ($\beta^{fog} = 13.36$, $k = 5$), and the turbulence is weak turbulence ($\alpha = 2.04$, $\beta = 1.1$) and strong turbulence ($\alpha = 3.78$, $\beta = 3.74$) as stated in [5] and [24], respectively.

In Figure 2, the effect of number of reflecting elements N in RIS is illustrated at various pointing error ξ values. The results depict that the increase in values of N significantly enhances the system outage probability. Also, at high value of ξ the system performance is better since high value of ξ signifies low sever effect of PE. It is noticed that the analytical results perfectly match the simulation ones which indicates the correctness of the derived outage probability.

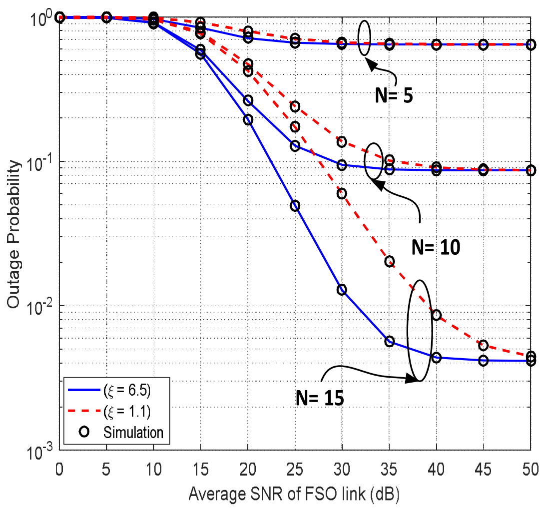

FIGURE 2. Impart of number of reflecting elements in RIS at different values of pointing errors under the weak turbulence and light fog for heterodyne detection.

The effect of AT and m parameter on the system performance under difference detection schemes is demonstrated in Figure 3. It can be observed that strong turbulence degrades the system performance with heterodyne detection offering better system performance. In addition, the results show that the increment in fading parameter m improves the system outage performance.

The impact of threshold SNR on the outage performance of the proposed system is illustrated in Figure 4 with and without hybrid FSO/RF links. It is demonstrated that the increase in threshold SNR deteriorates the system performance. Also, there is perfect match between the analytical and simulated results which shows the accuracy of the derived outage probability expression. The results also illustrate that the RIS-hybrid FSO/RF system performance is better than the system with RIS-FSO only.

Under Fog conditions, the performance of the system at different values of SI is presented in Figure 5. It can be deduced that the increase in self-interference at the relay degrades the performance of the system. Also, it can be observed that the system performs much better under the light fog than moderate fog.

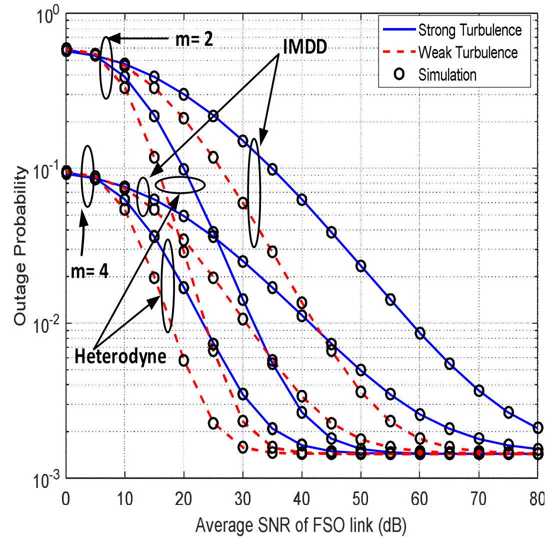

FIGURE 3. Effect of atmospheric turbulence and RF link fading parameter m under different detection techniques under the weak turbulence and light fog for heterodyne detection at $N = 10$.

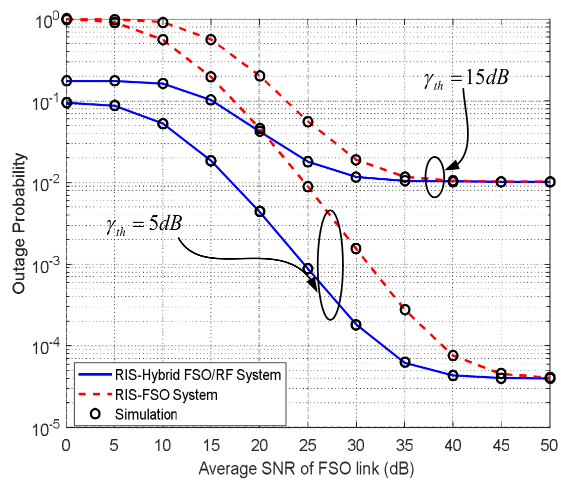

FIGURE 4. Influence of threshold SNR on the system performance under with and without hybrid FSO/RF links at weak turbulence and light fog for heterodyne detection $m = 4$.

5. CONCLUSION

This study examines the performance a full-duplex relay hybrid FSO/RF system with RSI-assisted source message transmission to the relay node under the AT, PE, and foggy channel conditions. It is also demonstrated that the number of reflecting elements in RIS has been found to greatly improve the system outage probability performance. In addition, the results depict that the system outage is strongly degraded by AT, PE, and foggy conditions. Also, it is found that the heterodyne detector system performs better than the IM/DD detector system under the same system and channel circumstances. Our results demonstrate the advantages of a hybrid FSO/RF link over an FSO link only.

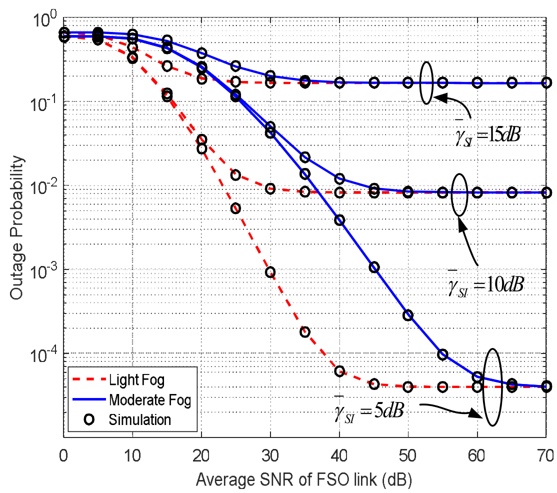

FIGURE 5. Impact of SI on the system performance at different fog conditions under the weak turbulence.

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