

Relay Selection in Energy Harvesting Aided Mixed RF/FSO System with Transmit Antenna Selection over Atmospheric Turbulence and Pointing Error

Kehinde O. Odeyemi* and Pius A. Owolawi

Abstract—In this paper, the performance of relay selection in an energy harvesting aided mixed radio frequency (RF)/free space optical (FSO) system with transmit antenna selection (TAS) over atmospheric turbulence and pointing error is presented. The source of multiple antennas employs TAS to send information to the destination via multiple relay nodes. Also, the energy-limited source uses selection combining technique to harvest energy from multiple relay nodes. As a result, all the relay nodes act as a wireless power transmitting node as well as data receiving node. Moreover, it assumes that the RF/FSO links follow Rayleigh/Malaga (M) distributions with non-zero boresight (NB) pointing error on the FSO link. Therefore, the system outage probability closed-form expression is then derived which is utilized to obtain the system throughput. In addition, the results demonstrate the significant effect of atmospheric turbulence and NB pointing error on the system performance with multiple relays, and source transmit antenna offers the system better performance. The accuracy of the derived expressions is thus validated through Monte Carlo simulations.

1. INTRODUCTION

Cooperative relaying technology has been known to extend the network coverage and overcome the issues of wireless channel impairments as a result of fading. This can be accomplished through the use of either amplified-and-forward (AF) and/or decode-and-forward (DF) relaying node(s) to transmit information between the source and destination [1]. Traditionally, RF cooperative systems suffer from vital limitations such as spectrum scarcity and limited data rate [2]. To alleviate these problems, FSO system has been proposed to be used in conjunction with the RF system because of its desirable features such as unlicensed spectrum, high security, and cheap cost of deployment [3]. Therefore, exploiting the complementary advantages of both links leads to a significant improvement in performance of wireless communication networks [4]. In this case, vast amount of research has been conducted on the performance of mixed RF/FSO systems. In [5], the performance of mixed RF/FSO dual-hop system under different detection schemes and relaying protocols was presented. The authors in [6] studied the performance of a mixed RF/FSO system under the assumption that the system channel follows the Nakagami-m/Gamma-Gamma distributions. Also, the performance of a relay assisted mixed FSO/RF system under the Malaga/ $k - \mu$ shadowed fading distributions channels was demonstrated in [7]. The review on the mixed RF/FSO system under the channel distributions, relaying protocols and detection schemes were well detailed and summarized in [8]. Nevertheless, these works were tailored towards a single relay node. In this case, considering multiple relay nodes between the source and destination leads to a significant improvement in the performance of a mixed RF/FSO system [9]. This therefore

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requires high energy consumption and strict synchronization at the receiver [10]. To overcome these limitations, relay selection technique has been suggested in literature where the best relay is selected for data transmission [11]. In [2], the performance of a DF mixed RF/FSO system under different relay selections was investigated with RF and FSO links subjected to generalized η - μ and Gamma-Gamma distributions, respectively. The authors further extended the work to an AF-based system under the channel characterizes in [12]. Moreover, a mixed RF/FSO system performance with outdated channel state information (CSI) under partial relay selection was studied in [9]. Also, the performance of a partial relay selection based AF mixed RF/FSO system with a direct RF link and outdated CSI was evaluated in [13]. A generalized M-distribution with NB pointing error was considered by the authors on the FSO link.

Recently, energy consumption in cooperative relaying network can also be reduced through energy harvesting, and this has attracted a lot of attention in the research community [1, 14]. This can be achieved by scavenging energy from renewable sources such as solar, vibration, wind, and other physical phenomena [14]. However, due to instability of these resources as a result of environmental challenges, harvesting energy from RF signals has been proposed as an alternative means to scavenge energy for wireless devices or sensors without depending on conventional power sources. This is as a result of the RF signal capability to simultaneously carry both the information and energy [15]. Therefore, to reduce energy consumption of a mixed RF/FSO system through energy harvesting, a few research studies have been done in this area. The throughput and outage probability analysis of a hybrid RF/FSO system with power allocation scheme was proposed in [16]. In [17], the dual-hop heterogeneous visible light communication (VLC)/RF communication system was investigated. Besides detecting the information over VLC link, the relay was able to harvest energy from the first-hop VLC link, by extracting the direct current component of the received optical signal. Also, the authors in [18] evaluated the performance of mixed RF/FSO systems where the battery-limited RF source harvested the required energy for information transmission from the relay node. They considered the direct link between the source and destination, and Rayleigh/Gamma-Gamma distributions are assumed for system channels. Moreover, the performance of a spectrum-sharing mixed multiple-input-single output (MISO) RF/FSO system with energy harvesting was studied in [4]. The channel model of the RF/FSO network is assumed to follow Nakagami-m/Malaga-M fading distributions.

While all the aforementioned works focused on a single relay mixed RF/FSO system, all also assumed a zero boresight (ZB) pointing error on the FSO link. Motivated by these facts, the performance of relay selection in an energy harvesting aided mixed RF/FSO system with TAS over atmospheric turbulence with NB pointing error is investigated. The source of multiple antennas employs TAS to send its information to the destination and utilizes SC to harvest energy from the relay nodes. Also, the concerned system channel is assumed to follow Rayleigh/Malaga (M) distributions. Therefore, the closed form expressions for the system outage probability and throughput are derived.

The rest of this paper is structured as follows. In Section 2, the system and channel models are presented. The performance analysis of the concerned system is illustrated. Numerical results and discussions are provided in Section 4. Finally, the concluding remarks are presented in Section 5.

2. SYSTEM AND CHANNEL MODELS

The model of a relay selection in a mixed RF/FSO system where an energy-constrained source (S) communicates with a destination (D) through the multiple relay nodes (R) is illustrated in Figure 1. Each of the relay nodes has two RF-type antennas, that is, an energy transmitting antenna (EA) and a data receiving antenna (DA). Based on this, the relay nodes function as wireless power transmitting nodes as well as data receiving nodes. The source is equipped with N_s multiple transmit antennas for energy harvesting as well as data transmission. Under data transmission, transmit antenna selection scheme is employed to send information to the destination via the selected relay node(s). During the energy harvesting, it is assumed that the source adopts selection combining technique to harvest the transmitting RF energy from the EA relay nodes. Each relay node employs a time switching protocol for power transfer, and the communication is divided into three consecutive time slots, that is, energy harvesting, information transmission, and information reception. The corresponding durations for the time slots are ρT , $(1 - \rho) T/2$, and $(1 - \rho) T/2$, respectively, where ρ is the harvesting time ratio

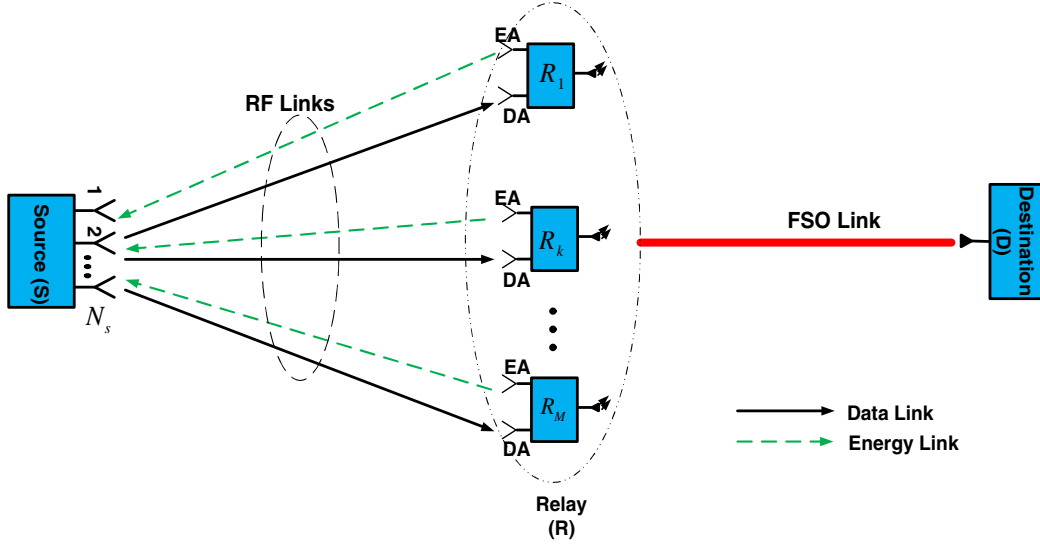


Figure 1. Relay selection in energy harvesting aided mixed RF/FSO system.

($0 \leq \rho \leq 1$), and T represents the total block duration. During the first time slot, the source harvests energy from the relay through the relay nodes EA, and SC scheme is employed to select the best RF signal to improve the amount of energy for the source.

The energy harvested by the source from the k -th relay through the EA over ρT duration can be expressed as [19]:

$$E_{h(k)} = \eta \rho P_{R(k)} T |h_{R(k)S}|^2 \quad (1)$$

where η is the energy harvesting efficiency, $h_{R(k)S}$ the channel coefficient of the R-to-S RF k -th relay link, and $P_{R(k)}$ the k -th relay transmission power. Thus, the average transmit power of the source used for information transmission can be obtained as [20]:

$$P_S = \frac{2E_{h(k)}}{(1-\rho)T} \triangleq \frac{2\eta\rho P_{R(k)} |h_{R(k)S}|^2}{(1-\rho)} \quad (2)$$

In completion of energy harvesting, the source uses the harvested energy to transmit the information to the k -th relay node DA over the time $(1-\rho)T/2$ by employing the TAS technique. Therefore, the received signal at the k -th relay DA can be given as:

$$y_R(t) = \sqrt{P_S} h_{SR(k)} s(t) + Z_{R(k)} \quad (3)$$

where $h_{SR(k)}$ is the channel coefficient between the selected transmit antenna and relay node DA. Since TAS is used at the source, the selection process is achieved by selection criterion $h_{SR(k)} = \arg |h_{SR(k),j}|^2$ with $h_{SR(k),j}$ denoting the channel coefficient between the j -th transmit antenna and k -th selected relay. $s(t)$ is the source information signal, and Z_R is the additive white Gaussian noise (AWGN) at the k th relay node with variance of σ_R^2 .

In the last duration of $(1-\tau)T/2$, the relay nodes amplify and convert the received information to optical energy and transmit the source information to the destination via the R-to-D FSO link. The received signal at the destination can be expressed as:

$$y_D(t) = \vartheta G y_R(t) h_{R(k)D} + Z_D \quad (4)$$

where $h_{R(k)D}$ is the channel coefficient between the k th selected relay node DA and the destination; ϑ is the electrical-to-optical conversion ratio; $G = 1 / \left(\sqrt{P_S |h_{SR(k)}|^2 + \sigma_R^2} \right)$; and Z_D denotes the AWGN at the destination with variance of σ_D^2 .

Based on Eq. (4), the received signal at the destination can be further expressed as:

$$y_D(t) = \frac{\vartheta h_{R(k)D}}{\sqrt{P_S |h_{SR(k)}|^2 + \sigma_R^2}} h_{SR(k)} s(t) + \frac{\vartheta h_{R(k)D}}{\sqrt{P_S |h_{SR(k)}|^2 + \sigma_R^2}} Z_{R(k)} + Z_D \quad (5)$$

Owing to deep fading, it is assumed that there is no direct link between the source and destination. Therefore, the RF links within the system are assumed to undergo Rayleigh fading distributions, and thus the PDF and CDF of the distribution can be given as [21]:

$$f_Z(\gamma) = \frac{1}{\bar{\gamma}_{PQ}} \exp\left(-\frac{\gamma}{\bar{\gamma}_{PQ}}\right) \quad (6)$$

and by integrating Eq. (6), the CDF is obtained as:

$$F_Z(\gamma) = 1 - \exp\left(-\frac{\gamma}{\bar{\gamma}_{PQ}}\right) \quad (7)$$

where $\bar{\gamma}_{PQ} = P_s/\sigma_R^2$ is the average SNR on the RF link with $PQ \in \{SR, RS\}$.

When the k -th relay node is selected as the best relay, the CDF of the R-to-S link can be obtained using the highest order statistics given in [22] as:

$$F_{RS}(\gamma) = (F_Z(\gamma))^{MN_S} \quad (8)$$

where M is the number of relay node

Putting Eq. (7) into Eq. (8), the CDF can be expressed through binomial expansion as [23, Eq. (1.111)]:

$$F_{RS}(\gamma) = 1 - \sum_{k=1}^{MN_S} \binom{MN_S}{k} (-1)^{k-1} \exp\left(-\frac{\gamma k}{\bar{\gamma}_{RS}}\right) \quad (9)$$

Then, the PDF can be expressed by differentiating Eq. (9) as:

$$f_{RS}(\gamma) = \sum_{k=0}^{MN_S} \binom{MN_S}{k} (-1)^{k-1} \left(\frac{k}{\bar{\gamma}_{RS}}\right) \exp\left(-\frac{\gamma k}{\bar{\gamma}_{RS}}\right) \quad (10)$$

Based on the principle of TAS technique, the PDF for the S-to-R link can be given as [24]:

$$f_{SR}(\gamma) = \sum_{q=0}^{N_s-1} \sum_{Mt_p} \binom{N_s-1}{q} \frac{(-1)^q N_s}{\Gamma(M) \bar{\gamma}_{SR}^\mu} \exp\left(-\frac{(q+1)\gamma}{\bar{\gamma}_{SR}}\right) \gamma^{\mu-1} \quad (11)$$

where N_S is the number of transmit antennas, and

$$\left\{ \begin{array}{l} \sum_{Mt_p} = \prod_{p=1}^{M-1} \left[\sum_{t_p=0}^{t_{p-1}} \binom{t_{p-1}}{t_p} \left(\frac{1}{p!}\right)^{t_p - t_{p+1}} \right] \\ \mu = Q_p + M \\ Q_p = \sum_{p=1}^{M-1} t_p \\ t_0 = q \\ t_M = 0 \end{array} \right. \quad (12)$$

Since the FSO link is assumed to follow M-distribution, the CDF of the R-to-D FSO link can be expressed as [4]:

$$F_{RD}(\gamma) = \frac{\xi_{mod}^2 \zeta}{2} \sum_{l=1}^{\beta} b_l G_{2,4}^{3,1} \left(\frac{B_l \gamma}{A_{mod} \bar{\gamma}_{RD}} \mid \begin{array}{l} 1, \xi_{mod}^2 + 1 \\ \xi_{mod}^2, \alpha, l, 0 \end{array} \right) \quad (13)$$

where α represents the positive effective number of large scale cells of the scattering process, and β is a natural number that denotes the amount of turbulence-induced fading, $b_l = a_l \left(\alpha\beta / \Theta\beta + \hat{\Omega} \right)^{-\alpha+l/2}$ with the parameters defined as [25]:

$$\begin{cases} \zeta = \frac{2\alpha^{\alpha/2}}{\Theta^{1+\alpha/2}\Gamma(\alpha)} \left(\frac{\Theta\beta}{\Theta\beta + \hat{\Omega}} \right)^{\frac{\alpha}{2}+\beta} \\ a_l = \left(\frac{\beta-1}{l-1} \right) \frac{(\Theta\beta + \hat{\Omega})^{1-l/2}}{(l-1)!} \left(\frac{\hat{\Omega}}{\Theta} \right)^{l-1} \left(\frac{\alpha}{\beta} \right)^{l/2} \end{cases} \quad (14)$$

where $\Gamma(\cdot)$ is the gamma function; $\Theta = 2b_o(1-\delta)$ is the classic scattering component average power; δ ($0 \leq \delta \leq 1$) represents the ratio of the power of the scattering component coupled with line-of-sight (LOS) to that of all scattering components; $\hat{\Omega} = \Omega + 2b_o\delta + 2\sqrt{2b_o\rho\Omega} \cos(\phi_A - \phi_B)$ denotes the average optical power of the coherent contributions, and it involves both the LOS component and the scattering component coupled with it, where Ω is the LOS term average power; $2b_o$ denotes the total average power; and $\phi_A - \phi_B$ are the deterministic phase of the LOS component and the scattering component coupled with it, respectively. Also, other parameters in Eq. (14) include $\xi_{mod} = w_{z,eq}/2\sigma_{mod}$ with $w_{z,eq}$ representing the equivalent beam radius at the receiver. σ_{mod} can be expressed in terms of Beckmann distribution parameters as [26]:

$$\sigma_{mod} = \left(\frac{3\mu_x^2\sigma_x^4 + 3\mu_y^2\sigma_y^4 + \sigma_x^6 + \sigma_y^6}{2} \right)^{1/6} \quad (15)$$

where $\sigma_x, \sigma_y, \mu_x,$ and μ_y are the Beckmann distribution parameters with $(\mu_x, \sigma_x,)$ denoting static boresight displacement and $(\mu_y, \sigma_y,)$ representing the standard deviations (jitter) for horizontal and vertical directions. Moreover, heterodyne detection is considered at the system destination, thus the instantaneous SNR for the FSO link can be given as $\gamma_{RD} = \bar{\gamma}_{RD}I$ and $I = A_{mod}\xi_{mod}^2 (\psi + \hat{\Omega}) \gamma / \bar{\gamma}_{RD} (\xi_{mod}^2 + 1)$. The expression for parameter A_{mod} can be expressed as:

$$A_{mod} = A_o \exp \left(\frac{1}{\xi_{mod}^2} - \frac{1}{2\xi_x^2} - \frac{1}{2\xi_y^2} - \frac{\mu_x^2}{2\xi_x^2\sigma_x^2} - \frac{\mu_y^2}{2\xi_y^2\sigma_y^2} \right) \quad (16)$$

where A_o is the fraction of the collected power at the center of the receiver. $\xi_x = w_{z,eq}/2\sigma_x,$ $\xi_y = w_{z,eq}/2\sigma_y$ and A_o is the amount of collected power at the center of receiver.

The instantaneous end to end SNR characterization for the system under the variable relay gain can be expressed as [5]:

$$\gamma_{eqk} \approx \frac{\gamma_{SR(k)}\gamma_{R(k)D}}{\gamma_{SR(k)} + \gamma_{R(k)D}} \leq \min \left(\gamma_{SR(k)}, \gamma_{R(k)D} \right) \quad (17)$$

where

$$\gamma_{SR(k)} = \frac{2\eta\rho P_{R(k)} |h_{R(k)S}|^2}{(1-\rho)\sigma_R^2} |h_{SR(k)}|^2 = \psi |h_{R(k)S}|^2 |h_{SR(k)}|^2 \quad (18)$$

with $\psi = \frac{2\eta\rho P_{R(k)}}{(1-\rho)N_0}$.

Therefore, the selection protocol to activate the k -th relay for transmission can be given as [27]:

$$\gamma_{eqk}^{\max} = \arg \max_{k=1\dots M} \{ \gamma_{eqk} \} \quad (19)$$

3. PERFORMANCE ANALYSIS

3.1. Outage Probability Analysis

The outage probability is defined as the probability that the SNR at destination goes below a predetermined outage threshold γ_{th} . Thus, the outage probability of the concerned system can be

expressed as [18]:

$$P_{out}(\gamma_{th}) = 1 - P_r(\gamma_{SR} > \gamma_{th}) P_r(\gamma_{RD} > \gamma_{th}) \quad (20)$$

Let $P_{RF}(\gamma_{th}) = P_r(\gamma_{SR} > \gamma_{th})$ and $P_{FSO}(\gamma_{th}) = P_r(\gamma_{RD} > \gamma_{th})$.

Then, Eq. (20) can be further expressed as:

$$P_{out}(\gamma_{th}) = 1 - P_{RF}(\gamma_{th}) P_{FSO}(\gamma_{th}) \quad (21)$$

Therefore, $P_{RF}(\gamma_{th})$ can be expressed as [18]:

$$P_{RF}(\gamma_{th}) = 1 - \int_0^\infty F_{RS} \left(\frac{\gamma_{th}}{\psi\gamma} \right) f_{SR}(\gamma) d\gamma \quad (22)$$

By substituting Eqs. (9) and (11) into Eq. (22), $P_{RF}(\gamma_{th})$ can be expressed as:

$$\begin{aligned} P_{RF}(\gamma_{th}) = & 1 - \sum_{q=0}^{N_s-1} \sum_{M t_p}^{N_s-1} \binom{N_s-1}{q} \frac{(-1)^q N_s}{\Gamma(M) \bar{\gamma}_{SR}^\mu} \underbrace{\int_0^\infty \gamma^{\mu-1} \exp\left(-\frac{(q+1)\gamma}{\bar{\gamma}_{SR}}\right) d\gamma}_{\Delta_1} \\ & + \sum_{q=0}^{N_s-1} \sum_{k=1}^{M N_s} \sum_{M t_p}^{N_s-1} \binom{N_s-1}{q} \binom{M N_s}{k} \frac{(-1)^{k+q-1} N_s}{\Gamma(M) \bar{\gamma}_{SR}^\mu} \underbrace{\int_0^\infty \gamma^{\mu-1} \exp\left(-\frac{k\gamma_{th}}{\psi \bar{\gamma}_{RS} \gamma}\right) \exp\left(-\frac{(q+1)\gamma}{\bar{\gamma}_{SR}}\right) d\gamma}_{\Delta_2} \quad (23) \end{aligned}$$

By applying the integral identity detailed in [23, Eq. (3.346(2))] to ψ_1 in Eq. (23),

$$\Delta_1 = \Gamma(\mu) \left(\frac{\bar{\gamma}_{SR}}{(q+1)} \right)^\mu \quad (24)$$

Using the integral identity defined in [23, Eq. (3.471(9))], the second term of Eq. (23) can be solved as:

$$\Delta_2 = 2 \left(\frac{k\gamma_{th} \bar{\gamma}_{SR}}{\psi \bar{\gamma}_{RS} (q+1)} \right)^{\frac{\mu}{2}} K_\mu \left(2 \sqrt{\frac{k\gamma_{th} (q+1)}{\psi \bar{\gamma}_{RS} \bar{\gamma}_{SR}}} \right) \quad (25)$$

where $K_v(\cdot)$ is the modified Bessel function of the v th order.

Substituting Eqs. (24) and (25) into Eq. (23), the closed-form expression $P_{RF}(\gamma_{th})$ can be expressed as:

$$\begin{aligned} P_{RF}(\gamma_{th}) = & 1 - \sum_{q=0}^{N_s-1} \sum_{M t_p}^{N_s-1} \binom{N_s-1}{q} \frac{(-1)^q N_s}{\Gamma(M) \bar{\gamma}_{SR}^\mu} \left(\frac{\bar{\gamma}_{SR}}{(q+1)} \right)^\mu \Gamma(\mu) \\ & + \sum_{q=0}^{N_s-1} \sum_{k=1}^{M N_s} \sum_{M t_p}^{N_s-1} \binom{N_s-1}{q} \binom{M N_s}{k} \frac{2(-1)^{k+q-1} N_s}{\Gamma(M) \bar{\gamma}_{SR}^\mu} \left(\frac{k\gamma_{th} \bar{\gamma}_{SR}}{\psi \bar{\gamma}_{RS} (q+1)} \right)^{\frac{\mu}{2}} K_\mu \left(2 \sqrt{\frac{k\gamma_{th} (q+1)}{\psi \bar{\gamma}_{RS} \bar{\gamma}_{SR}}} \right) \quad (26) \end{aligned}$$

Moreover, the $P_{FSO}(\gamma_{th})$ can be expressed as [18]:

$$P_{FSO}(\gamma_{th}) = 1 - F_{RD}(\gamma_{th}) \quad (27)$$

Then, by substituting (13) into (27), $P_{FSO}(\gamma_{th})$ can be obtained as:

$$P_{FSO}(\gamma_{th}) = 1 - \frac{\xi^2 \zeta_{mod}}{2} \sum_{l=1}^{\beta} b_l G_{2,4}^{3,1} \left(\frac{B_l \gamma_{th}}{A_{mod} \bar{\gamma}_{RD}} \middle| \begin{matrix} 1, \xi^2 \zeta_{mod} + 1 \\ \xi^2 \zeta_{mod}, \alpha, l, 0 \end{matrix} \right) \quad (28)$$

Thus, the outage probability of the concerned system can be obtained by putting Eqs. (26) and (28)

into Eq. (21) as follows:

$$\begin{aligned}
 P_{out}(\gamma_{th}) &= \sum_{q=0}^{N_s-1} \sum_{Mt_p} \binom{N_s-1}{q} \frac{(-1)^q N_s}{\Gamma(M) \bar{\gamma}_{SR}^\mu} \left(\frac{\bar{\gamma}_{SR}}{(q+1)} \right)^\mu \Gamma(\mu) \\
 &- \sum_{q=0}^{N_s-1} \sum_{k=1}^{MN_S} \sum_{Mt_p} \binom{N_s-1}{q} \binom{MN_S}{k} \frac{2(-1)^{k+q-1} N_s}{\Gamma(M) \bar{\gamma}_{SR}^\mu} \left(\frac{k\gamma_{th} \bar{\gamma}_{SR}}{\psi \bar{\gamma}_{RS} (q+1)} \right)^{\frac{\mu}{2}} K_\mu \left(2\sqrt{\frac{k\gamma_{th} (q+1)}{\psi \bar{\gamma}_{RS} \bar{\gamma}_{SR}}} \right) \\
 &+ \frac{\xi_{mod}^2 \zeta}{2} \sum_{l=1}^{\beta} b_l G_{2,4}^{3,1} \left(\frac{B_l \gamma_{th}}{A_{mod} \bar{\gamma}_{RD}} \mid \begin{matrix} 1, \xi_{mod}^2 + 1 \\ \xi_{mod}^2, \alpha, l, 0 \end{matrix} \right) \left[1 - \sum_{q=0}^{N_s-1} \sum_{Mt_p} \binom{N_s-1}{q} \frac{(-1)^q N_s}{\Gamma(M) \bar{\gamma}_{SR}^\mu} \left(\frac{\bar{\gamma}_{SR}}{(q+1)} \right)^\mu \Gamma(\mu) \right. \\
 &\left. + \sum_{q=0}^{N_s-1} \sum_{k=1}^{MN_S} \sum_{Mt_p} \binom{N_s-1}{q} \binom{MN_S}{k} \frac{2(-1)^{k+q-1} N_s}{\Gamma(M) \bar{\gamma}_{SR}^\mu} \left(\frac{k\gamma_{th} \bar{\gamma}_{SR}}{\psi \bar{\gamma}_{RS} (q+1)} \right)^{\frac{\mu}{2}} K_\mu \left(2\sqrt{\frac{k\gamma_{th} (q+1)}{\psi \bar{\gamma}_{RS} \bar{\gamma}_{SR}}} \right) \right] \quad (29)
 \end{aligned}$$

3.2. Throughput Analysis

In this study, system throughput closed form expression is determined based on the delay-limited transmission mode. This is derived through the system outage probability at a fixed source transmission rate of Rbits/s/Hz. Therefore, at a fixed transmission rate with effective communication time of $(1 - \rho)T/2$, the throughput τ for the concerned system from the source to destination can be expressed as [28]:

$$\tau = (1 - P_{out}) R \frac{(1 - \rho) T/2 R}{T} \frac{1}{2} (1 - P_{out}) (1 - \rho) \quad (30)$$

where P_{out} is the derived system outage probability closed-form given in Eq. (29).

4. NUMERICAL RESULTS AND DISCUSSIONS

In this section, the outage probability and throughput analytical results for the concerned system under the influence of atmospheric turbulence with ZB pointing error are presented using Eqs. (29) and (30) respectively. The correctness of these derived expressions is validated with Monte Carlo simulation, and 1000 iterations are used during the simulation for specific error of 10^{-8} . Regarding the atmospheric turbulence conditions on the R-to-D FSO link, the strong level is given as $\alpha = 2.296$, $\beta = 2$ while the weak levels are set as $\alpha = 8.0$, $\beta = 4$ [29]. M -distribution parameters are set to $\delta = 0.596\Omega = 1.3265$, $b_o = 0.1079$, $\phi_1 - \phi_2 = \pi/2$. Two pointing errors scenarios are considered, and this includes zero boresight (ZB) and non-zero boresight (NB). Following the approach in [30], it is assumed that the static boresight displacement and the standard deviations for horizontal and vertical directions are defined to be $\mu_x/a = 0$, $\mu_y/a = 0$, $\sigma_x/a = 2$ and $\sigma_y/a = 1$ for ZB pointing error while $\mu_x/a = 2$, $\mu_y/a = 4$, $\sigma_x/a = 2$, and $\sigma_y/a = 1$ are assumed for NB pointing error. Except stated otherwise, the simulation parameters are set to: $w_z/a = 5$, $\bar{\gamma}_{SR} = \bar{\gamma}_{RS} = 5$ dB, $N_s = 2$, $\rho = 0.2$ and $R = 2$ bits/s/Hz.

In Figure 2, the impact of number of source transmit antennas on the system performance is illustrated under different pointing error scenarios. It can be deduced that as the source antenna increases the system outage performance is lowered. As expected, the results depict that NB pointing error has strong severe effect on the system performance compared to ZB pointing error. Also, the analytical results provide a perfect match to the simulation results which show the accuracy of the derived outage expression.

The effect of number of relay nodes on the outage performance is presented in Figure 3. Again, the analytical results perfectly match with the simulation ones. Also, the results show that the system outage performance degrades as the atmospheric turbulence becomes severe. It can be deduced that an increase in number of relay nodes enhances the system outage probability performance.

The system outage performances under different values of outage threshold γ_{th} and ρ are demonstrated in Figure 4. The results show that as the value of ρ increases, the outage performance becomes better. This is because large amount of energy is harvested by the source to process and

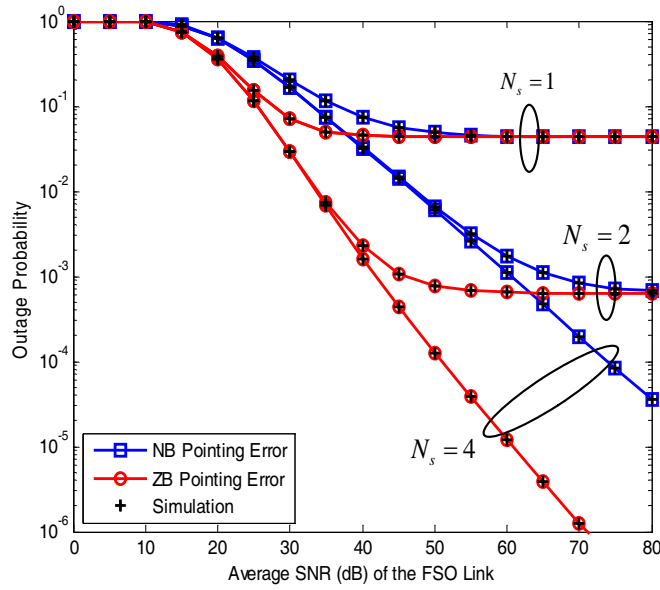


Figure 2. Impact of pointing error on the system performance under different number of source transmit antenna at strong turbulence when $\rho = 2$, $M = 2$ and $\gamma_{th} = 5$ dB.

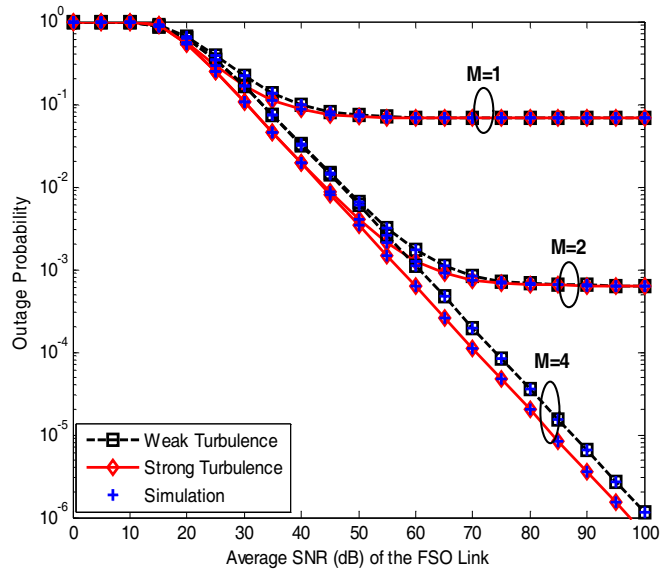


Figure 3. Effect of number of relay on the system performance under different turbulence conditions at NB pointing error when $\rho = 2$, $N_s = 2$ and $\gamma_{th} = 5$ dB.

transmits information to the destination. According to the result, it can be seen that at low outage threshold value, the system performs better than that at high value of outage threshold under the same values of ρ .

In Figure 5, the throughput performances of the system under different values of N_s and pointing error conditions at strong turbulence are presented. It can be depicted that the pointing error significantly deteriorates the system throughput with ZB pointing error having strong effect on the system compared with NB pointing error. There is perfect agreement between the analytical and simulation results, which indicates the accuracy of the derived throughput expression. Expectedly, the

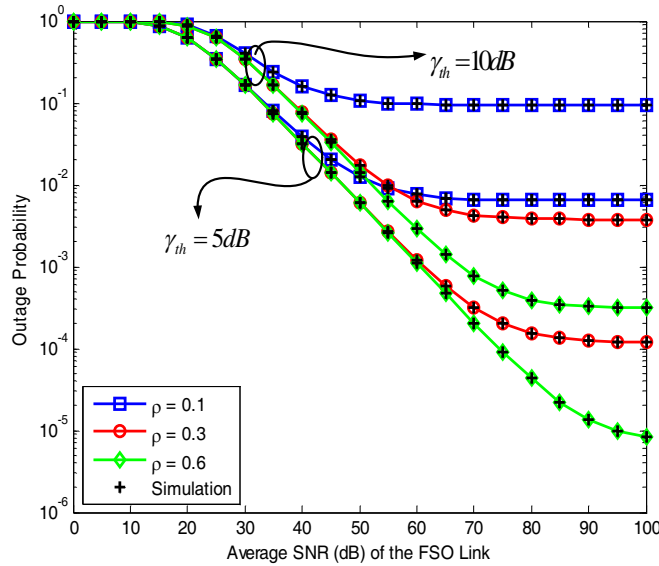


Figure 4. System performance under different outage threshold and values of ρ at strong turbulence and NB pointing error when $N_s = 2$ and $M = 2$.

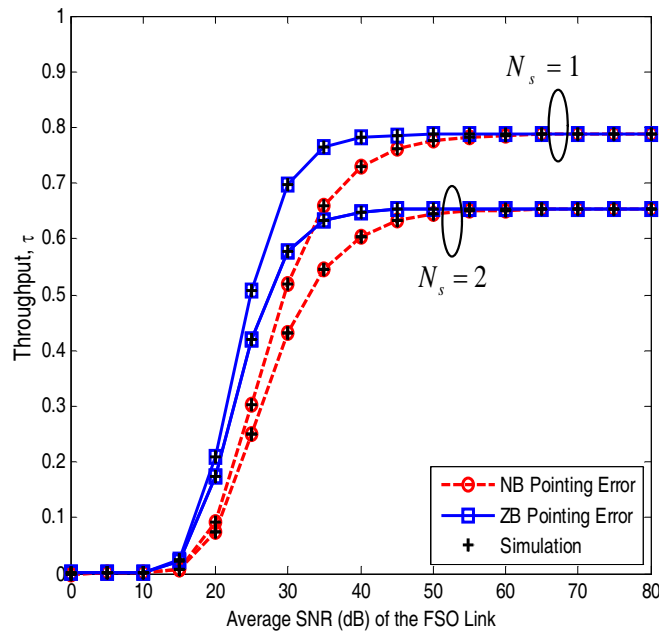


Figure 5. Throughput performance of the system under different values of N_s and pointing error conditions when $M = 2$, $R = 2$ bits/s/Hz and $\gamma_{th} = 10$ dB.

increase in the number of source transmit antennas enhances the system throughput performance.

The performance of the system throughput as a function of ρ is depicted in Figure 6 under different turbulence conditions. The results show that the increase in the number of relay nodes offers the system better throughput performance. Moreover, the result indicates that there is an optimum ρ that provides maximum throughput performance for the concerned system for each relay node.

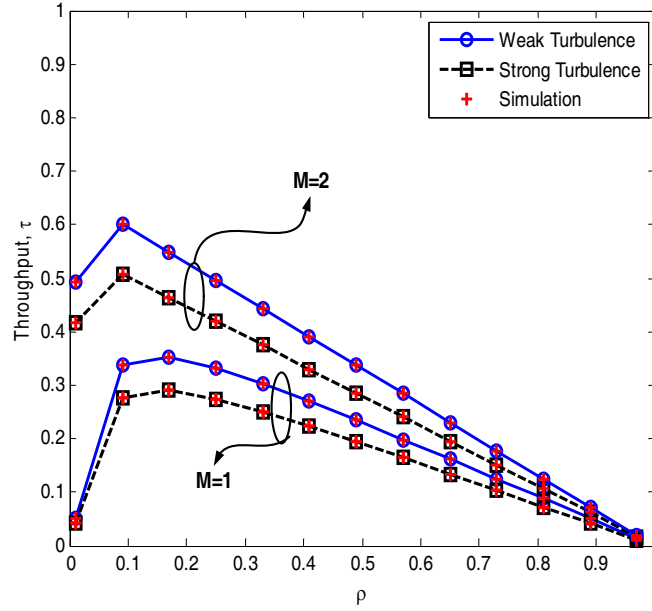


Figure 6. Throughput as a function ρ under different number of relay nodes and turbulence conditions when $N_s = 2$, $\gamma_{th} = 5$ dB and $\bar{\gamma}_{fso} = 20$ dB.

5. CONCLUSION

In this paper, the performance of relay selection in an energy harvesting aided mixed RF/FSO system over atmospheric turbulence and pointing error is presented. Transmit antenna selection and SC diversity scheme are respectively used by source to transmit information to destination and harvest energy from the relay node. The outage probability and throughput closed-form expressions are derived for the system. Also, the simulation results agree well with analytical ones, which indicates the accuracy of the derived expressions. The results depict that the atmospheric turbulence and ZB pointing error strongly degrade the system performance. Under the influence of pointing error, NB pointing error has much effect on the system performance compared with ZB pointing error. Moreover, the results illustrate that the increase in the number of source antennas as well as relay nodes significantly improves the system performance.

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