# Computing Outage Probability for a Mixed FSO-RF System with Energy Harvesting in Downlink Transformation

Ali Asgari-Forooshani[1], Masoudreza Aghabozorgi[1*]
1- Department of Electrical Engineering, Yazd University, Yazd 89195-741, Iran.
Email: asgari@stu.yazd.ac.ir
Email: aghabozorgi@yazd.ac.ir (Corresponding author)

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**ABSTRACT:**
A new emerging solution to prolong the lifetime of the energy-constrained wireless networks is energy harvesting. In this paper, an Amplify-and-Forward (AF) relaying network in downlink phase is proposed. The relay harvests energy through Free Space Optical (FSO) link from the source and uses it to forward information to the destination through the RF link. In addition, there is a direct RF link between the source and destination. The FSO link experiences Gamma-Gamma atmospheric turbulence conditions with pointing errors and Rayleigh fading is considered for RF channels. In this system, a closed-form expression for outage probability in the form of Meijer's-G function is derived.

**KEYWORDS:** Free Space Optical Communication, Cooperative Communication, Energy Harvesting, Radio Frequency and Mixed FSO-RF.

## 1. INTRODUCTION

Free space optical (FSO) communication is a new technology for transferring information with fiber-like data rate. FSO systems use lasers or light emitting diodes (LEDs) with considerably lower cost, compared to fiber links, and without extensive installation needs such as digging [1]. Because of the propagation nature of the FSO systems, that is line-of-sight (LOS) with narrow beams, they do not interfere with other systems such as cellular networks. Therefore, the FSO systems can be installed beside of the other systems, without need to any changes. Moreover, the FSO spectrums are license free and so these systems do not have the problem of the spectrum scarcity. Because of the above advantages, research on FSO systems has received significant attention recently [2-6]. The combination of the FSO and the radio frequency (RF) systems in a mixed RF-FSO setup is an interesting innovation that can unties the bottleneck problem between RF access networks and fiber optic based backbone networks [7]. The mixed RF-FSO systems have the both advantages of the RF systems and the FSO systems together. There are a lot of literatures on the investigation of the performance of mixed RF-FSO systems [7-11]. For example, in [11] the impact of pointing errors on the performance of mixed RF-FSO dual-hop transmission systems was investigated. In that paper, the FSO and RF channels were modeled by Gamma-Gamma and Rayleigh fading, respectively and the expressions for average bit error probability (BEP), average symbol error probability (SEP) and ergodic capacity were derived. In [7] the authors analyzed the performance of mixed FR-FSO cooperative systems considering the effect of cochannel interference at both relay and destination.

From another perspective, energy harvesting from ambient sources such as RF signals, solar, wind, vibration, thermoelectric effects or other physical phenomena [12], [13], is a new emerging solution to prolong the lifetime of the energy-constrained wireless networks. For example, in wireless sensor networks (WSNs), the nodes are usually powered by batteries and as the battery of one node becomes empty, the node expires. In this situation replacing the node or its battery is troublesome and costly, while if the nodes are capable of harvesting energy, the system will get rid of this problem. Another example is cellular network in which the nodes, because of their mobility, are not connected to the continuous power supply. There are many researches papers that investigate energy harvesting. For example, a network architecture for RF stations charging in a cellular network was presented in [14]. Authors in [15] introduced relay protocols for wireless energy harvesting and information processing. A harvest-then-transmit (HTT) protocol for wireless power broadcasting system was proposed in [16]. Authors in [17], [18] set up a trade of between energy and information transferring to optimize performance of a wireless system. Different techniques to achieve power transfer efficiency in mobile applications applied in [19], [20]. The harvest-then-cooperate protocol was proposed in [21] and it was shown that this one outperforms than HTT protocol. Most articles investigated energy harvesting from the RF link. For example, the authors in [22] analyzed the performance of mixed RF/FSO cooperative systems with wireless power transfer through RF link in uplink scenario. There are few works on energy harvesting from the FSO link and it motivates the authors of this paper to introduce a system model in which the energy be harvested from the FSO link.

In this paper, a system model for energy harvesting in mixed FSO-RF system is introduced, in which a source node sends its information to the destination through a relay and in a direct mode. Amplify and forward (AF) with variable gain technique is considered for relaying and delay limited time-switching model, which is more practical in real applications, for energy harvesting. The Gamma-Gamma distribution is proposed for FSO link, since it is a prevalent choice for statistical turbulence channel model with its ability to better reflect a wider range of turbulence conditions [7]. RF links are assumed to experience Rayleigh fading, which is a typical model for multi-path RF channels.

The contributions of this work are summarized as follows. The downlink transmission of mixed FSO-RF cooperative systems is studied. The considered scenario includes three nodes: One source (S), one relay (R) and one destination (S). The link between source and relay is FSO and the links between relay-destination and source-destination are RF. The relay receives electromagnetic signal from the source and converts it to electrical power and uses it to forward information to the destination. The harmonic mean SNR between source-relay and relay-destination is computed and consequently the overall source-relay-destination harmonic mean SNR will be derived. For considered scenario, the closed-form expressions for outage probability in terms of Meijer's-G function are derived and the theoretical result is verified by Monte-Carlo simulations. The effects of different parameters on the performance of the system is studied.

The remainder of the paper is organized as follows. In section 2 the system and channels models are introduced. In section 3 the closed-form expressions of outage probability are extracted. Section 4 represents the numerical results and finally conclusion is presente in section 5.

Notation: throughout this paper $f_x(.)$ and $F_x(.)$ denote the probability density function (PDF) and cumulative distribution function (CDF) of a random variable $x$. $\Gamma(x)=\int_0^\infty e^{-t}t^{x-1}dt$ is the gamma function [23]. The operator $\mathbb{E}[.]$ stands for expectation, while $\Pr[.]$ denotes probability.

## 2. SYSTEM AND CHANNEL MODEL

A scenario with three nodes is considered: A source node (S), a relay node (R) and a destination node (D). This scenario is illustrated in Fig. 1. The importance of such system model in real-world applications is to solve last mile problem. There exists a connectivity gap between the back-bone network and the last-mile access network where wireless users can access the network resources. They have a limited battery capability and should harvest energy. The last mile connectivity can be delivered via a high-speed FSO link. For instance, in some areas where the fiber optic structure is not developed. A high bandwidth link requires huge amount of economic resources to dig up the current brown-field, while the FSO link is easy-to-install and cost-effective.

The downlink scenario is investigated where the source node (a base station) sends its information to the destination (a mobile user) through the relay. The S-R link is an FSO link, and the R-D and S-D links are RF links. The relay harvests energy from the source and uses it to transform information. HTC protocol is employed for wireless power transfer. As shown in Fig. 2, each transmission block of time T is divided into three slots by using variable $0<\tau<1$: first time-slot for energy transferring from S to R ($\tau$ T amount of time-slot for wireless power transfer), second time-slot for information transferring from S to R and D, and third slot for transforming information from R to D ($T-\tau T$ amount of time-slot for information transmission which is divided to $\frac{T-\tau T}{2}$ for each phase of information transmission).

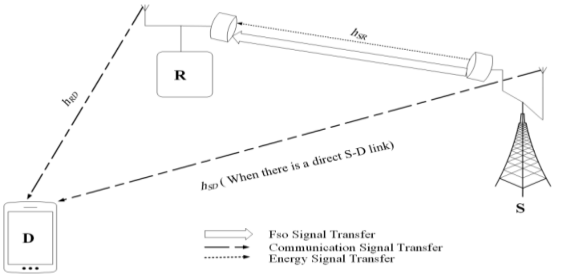

**Fig. 1**. System model of a mixed FSO-RF communications system with energy harvesting.

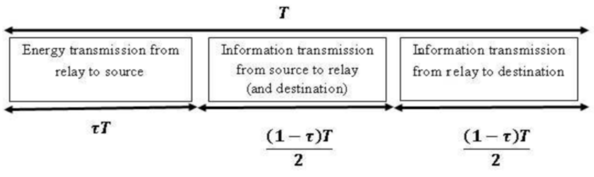

**Fig. 2**. Diagram of the harvest-then-cooperate protocol.

The harvested energy from relay by source is given by:

$$E_R = \eta\rho\tau T P_S \,|\, h_{SR} \,|^2 \tag{1}$$

Where $0 < \eta < 1$ is the energy harvesting efficiency and $\rho$ is optical-to-electrical conversion ratio; $P_S$ is the source transmission power and $h_{\mathrm{SR}}$ is the coefficient of the S-R channel. With looking at Fig. 2 and using (1), the transmitted signal power from relay is equal to:

$$P_R = \frac{E_R}{(1-\tau)T\ /\ 2} = \frac{2\eta\tau P_S \,|\, h_{SR} \,|^2}{(1-\tau)} \tag{2}$$

For cooperative communications, the AF relaying protocol with variable gain $G = \frac{1}{\sqrt{P_S |h_{SR}|^2 + N_0}}$ is assumed, where $N_0$ is the power of the noise. It is assumed that all receivers endure zero-mean additive white Gaussian noise (AWGN) [24]. The Rayleigh distribution is considered for statistical model of channel fading in the RF link. The average SNR in RF links are defined as $\overline{\gamma_{RD}} = \frac{P_R}{N_0}$ and $\overline{\gamma_{SD}} = \frac{P_S}{N_0}$, while the instantaneous SNRs are equal to $\gamma_{RD} = \overline{\gamma_{RD}} |h_{RD}|^2$ and $\gamma_{SD} = \overline{\gamma_{SD}} |h_{SD}|^2$, where $h_{RD}$ and $h_{SD}$ follow Exponential distribution with the mean $\sigma_{RD}^2$ and $\sigma_{SD}^2$. Therefore, the PDF and CDF of the RD link and SD link can be written as:

$$f_{|h_{RD}|^2}(x) = \sigma_{RD}^{-2} e^{-\sigma_{RD}^{-2} x}, F_{|h_{RD}|^2}(x) = 1 - e^{-\sigma_{RD}^{-2} x} \tag{3}$$

$$f_{|h_{SD}|^2}(x) = \sigma_{SD}^{-2} e^{-\sigma_{SD}^{-2} x}, F_{|h_{SD}|^2}(x) = 1 - e^{-\sigma_{SD}^{-2} x} \tag{4}$$

The instantaneous received irradiance of FSO link is defined as $I = I_a I_P$, where $I_a$ demonstrates atmospheric turbulence, while $I_P$ stands for pointing error. For the FSO link, we use Gamma-Gamma turbulence with Rayleigh distributed pointing error impairments and intensity modulation/direct detection (IM/DD) method for the FSO receiver. Then by assuming $\gamma_{SR} = \frac{P_S}{N_0} |h_{SR}|^2.\mathrm{T}$, the PDF of instantaneous SNR can be expressed as [11]:

$$f_{\gamma_{SR}}(\gamma_{SR}) = \frac{\xi^2}{2\gamma_{SR}\Gamma(\alpha)\Gamma(\beta)} G_{1,3}^{3,0}\left[\alpha\beta\sqrt{\frac{\gamma_{SR}}{\overline{\gamma_{SR}}}}\,\middle|\, \begin{matrix} \xi^2+1 \\ \xi^2, \alpha, \beta \end{matrix}\right] \tag{5}$$

Where, $\overline{\gamma_{SR}} = \frac{A_0^2 P_S}{N_0}$ with $A_0$ is a constant term that defines the pointing loss and $N_0$ is variance of ZMAWGN at the destination. $G_{p,q}^{m,n}[.]$ is the Meijer's-G function defined in [23, Eq. (9.301)] and $\overline{\gamma_{SR}}$ is the average SNR of S-R link. $\alpha$ and $\beta$ are the Gamma-Gamma turbulence parameters which are related to the severity of atmospheric conditions [25], and $\xi$ is the ratio between the equivalent beam radius at the receiver and the pointing error displacement standard deviation at receiver [26]. By integrating (4) over $\gamma_{SR}$ and using [27, Eq. (07.34.21.0001.01)], the CDF of $\gamma_{SR}$ is obtained as:

$$F_{\gamma_{SR}}(\gamma_{th}) = \frac{\xi^2}{\Gamma(\alpha)\Gamma(\beta)} G_{2,4}^{3,1}\left[\alpha\beta\sqrt{\frac{\gamma_{th}}{\overline{\gamma_{SR}}}}\,\middle|\, \begin{matrix} 1,\ \xi^2+1 \\ \xi^2, \alpha, \beta, 0 \end{matrix}\right] \tag{6}$$

## 3. COMPUTING OUTAGE PROBABILITY OF THE SYSTEM

The received RF signal at the relay can be written as:

$$y_{\mathrm{R}} = h_{\mathrm{SR}} x + n_{\mathrm{R}}$$

(7)

Where, $x$ is the modulation symbol of the source with an average power of $\mathbb{E}[|x|^2]$, $h_{SR}$ denotes the coefficient of source-relay link and $n_R$ is zero-mean additive white Gaussian noise (ZMAWGN) at relay with variance of $N_0$. The relay converts the optical signal into electrical signal, amplifies the received signal by a variable gain G and sends it to the destination. The received signal through the relay at the destination can be written as:

$$\begin{aligned} y_{\mathrm{D}} &= \rho h_{\mathrm{RD}} G y_{\mathrm{R}} + n_{\mathrm{D}} = \rho h_{\mathrm{RD}} G h_{\mathrm{SR}} x + \rho h_{\mathrm{RD}} G n_{\mathrm{R}} + n_{\mathrm{D}} \\ &= \frac{\rho h_{\mathrm{RD}}}{\sqrt{P_S \,|\, h_{SR} \,|^2 + N_0}} h_{\mathrm{SR}} x + \frac{\rho h_{\mathrm{RD}}}{\sqrt{P_S \,|\, h_{SR} \,|^2 + N_0}} n_{\mathrm{R}} + n_{\mathrm{D}} \end{aligned} \tag{8}$$

Where, $n_D$ is ZMAWGN at the destination. For variable gain relaying technique, the overall SNR for S-R-D path is given by [7]:

$$\gamma_{SRD} = \frac{\gamma_{SR}\gamma_{RD}}{\gamma_{SR} + \gamma_{RD} + 1} \tag{9}$$

Where

$$\begin{aligned} \gamma_{RD} &= \overline{\gamma_{RD}} \,|\, h_{RD} \,|^2 = \frac{P_R}{N_0} \,|\, h_{RD} \,|^2 = \frac{2\eta\tau P_S \,|\, h_{SR} \,|^2}{(1-\tau) N_0} \,|\, h_{RD} \,|^2 \\ &= \mu_1 \,|\, h_{SR} \,|^2 |\, h_{RD} \,|^2 \end{aligned} \tag{10}$$

While $\mu_1 = \frac{2\eta\tau P_S}{(1-\tau)N_0}$.

Similar to (7), the received signal through the S-D link at the destination can be written as:

$$y_{\mathrm{SD}} = h_{\mathrm{SD}}x + n_{\mathrm{D}} \tag{11}$$

Where, $h_{SD}$ denotes the fading coefficient of source- destination link. In this scenario, we have two signals at the receiver and consequently two SNRs, one the SNR of S-R-D path introduced in (9), other the SNR of S-D link which is defined as follow:

$$\begin{aligned}\gamma_{SD} &= \overline{\gamma_{SD}}\,|h_{SD}|^2 = \frac{P_S}{N_0}|h_{SD}|^2 = \frac{2\eta\tau P_R\,|h_{RS}|^2}{(1-\tau)N_0}|h_{SD}|^2 \\ &= \mu_1|h_{RS}|^2|h_{SD}|^2\end{aligned} \tag{12}$$

The selection combining (SC) method at the destination is supposed which selects signal from the path which has the maximum overall SNR [28]. Thus the final SNR can be written as:

$$\gamma_{final} = \max(\gamma_{SRD}, \gamma_{SD}) \tag{13}$$

The probability that the overall SNR is lower than a given threshold ,$\gamma_{th}$, is defined as the outage probability, thus we have:

$$\begin{aligned}F_{(\gamma_{final})}(\gamma_{th}) &\approx \Pr(\gamma_{final} < \gamma_{th}) = F_{\gamma_{final}}(\gamma_{th}) \\ &= \Pr\big(\max(\gamma_{SRD}, \gamma_{SD}) < \gamma_{th}\big) \\ &= \Pr(\gamma_{SRD} < \gamma_{th}, \gamma_{SD} < \gamma_{th}) \\ &= \Pr(\gamma_{SRD} < \gamma_{th})\Pr(\gamma_{SD} < \gamma_{th})\end{aligned} \tag{14}$$

The above expression is the same CDF of $\gamma_{final}$ evaluated at $\gamma = \gamma_{th}$, therefore $P_{out}(\gamma_{th}) = F_{(\gamma_{final})}(\gamma_{th})$.

Let define $p_1 = \Pr(\gamma_{SRD} < \gamma_{th})$ and $p_2 = \Pr(\gamma_{SD} < \gamma_{th})$, thus we have:

$$P_{out}(\gamma_{th}) = p_1 p_2 \tag{15}$$

For simplicity, (9) can be approximated as follows:

$$\gamma_{SRD} = \frac{\gamma_{SR}\gamma_{RD}}{\gamma_{SR} + \gamma_{RD} + 1} \approx \frac{\gamma_{SR}\gamma_{RD}}{\gamma_{SR} + \gamma_{RD}} \tag{16}$$

This approximation is completely matched in high SNRs. By defining $\mu_2 = \frac{P_S}{N_0}$ and substituting (10) in (16) we have:

$$\gamma_{SRD} \approx \frac{\mu_2|h_{SR}|^2\mu_1|h_{SR}|^2|h_{RD}|^2}{\mu_2|h_{SR}|^2 + \mu_1|h_{SR}|^2|h_{RD}|^2} = \frac{\mu_2\mu_1|h_{SR}|^2|h_{RD}|^2}{\mu_2 + \mu_1|h_{RD}|^2} \tag{17}$$

By using some probability theories, we have:

$$\begin{aligned}p_1 = \int_0^\infty &Pr\left[\left(\frac{\mu_2\mu_1|h_{SR}|^2|h_{RD}|^2}{\mu_2 + \mu_1|h_{RD}|^2}\right)\langle \gamma_{th}\,\big||h_{SR}|^2\right] \\ &\times f_{|h_{SR}|^2}\left(|h_{SR}|^2\right)d\,|h_{SR}|^2\end{aligned} \tag{18}$$

By using (3) we have:

$$Pr\left[\left(\frac{\mu_2\mu_1|h_{SR}|^2|h_{RD}|^2}{\mu_2 + \mu_1|h_{RD}|^2}\right) < \gamma_{th}\big||h_{SR}|^2\right] =$$

$$1 - e^{\frac{\mu_2\gamma_{th}}{\sigma_{RD}^2\mu_1(\mu_2|h_{SR}|^2 - \gamma_{th})}} \tag{19}$$

By employing [27, Eq. (07.34.03.0046.01)] and [27, Eq. (07.34.16.0002.01)], we can rewrite the above expression as:

$$Pr\left[\left(\frac{\mu_2\mu_1|h_{SR}|^2|h_{RD}|^2}{\mu_2 + \mu_1|h_{RD}|^2}\right) < \gamma_{th}\big||h_{SR}|^2\right] =$$

$$1 - G_{1,0}^{0,1}\left[\frac{\sigma_{RD}^2\mu_1(\mu_2|h_{SR}|^2 - \gamma_{th})}{\mu_2\gamma_{th}}\Big|\begin{matrix}1\\ -\end{matrix}\right] \tag{20}$$

With assumption that $\gamma_{SR} = \mu_2|h_{SR}|^2 \gg \gamma_{th}$, which is exact in high SNRs, we can simplify above expression as:

$$Pr\left[\left(\frac{\mu_2\mu_1|h_{SR}|^2|h_{RD}|^2}{\mu_2 + \mu_1|h_{RD}|^2}\right) < \gamma_{th}\big||h_{SR}|^2\right] =$$

$$1 - G_{1,0}^{0,1}\left[\frac{\sigma_{RD}^2\mu_1|h_{SR}|^2}{\gamma_{th}}\Big|\begin{matrix}1\\ -\end{matrix}\right] \tag{21}$$

By substituting (21) in (18) we have:

$$\begin{aligned}P_{out}(\gamma_{th}) = 1 - \frac{\xi^2}{2\Gamma(\alpha)\Gamma(\beta)}\int_0^\infty &G_{1,0}^{0,1}\left[\frac{\sigma_{RD}^2\mu_1|h_{SR}|^2}{\gamma_{th}}\Bigg|\begin{matrix}1\\ -\end{matrix}\right] \\ \times G_{1,3}^{3,0}&\left[\alpha\beta\sqrt{|h_{SR}|^2}\,\Bigg|\begin{matrix}\xi^2+1\\ \xi^2,\alpha,\beta\end{matrix}\right]d\,|h_{SR}|^2\end{aligned} \tag{22}$$

By employing [27, Eq. (07.34.21.0011.01)], we can compute above integral as:

$$p_1 = 1 - \frac{\xi^2\times 2^{\alpha+\beta-1}}{4\pi\Gamma(\alpha)\Gamma(\beta)}G_{2,7}^{7,0}\left[\frac{\alpha^2\beta^2\gamma_{th}}{16\mu_1\sigma_{RD}^2}\Bigg|\begin{matrix}\frac{\xi^2+1}{2},\frac{\xi^2+2}{2}\\ \frac{\xi^2}{2},\frac{\xi^2+1}{2},\frac{\alpha}{2},\frac{\alpha+1}{2},\frac{\beta}{2},\frac{\beta+1}{2},0\end{matrix}\right] \tag{23}$$

By using (4) and (12), $p_2$ can be derived as:

$$p_2 = 1 - e^{-\frac{\gamma_{th}}{\mu_2\sigma_{SD}^2}} \tag{24}$$

By employing [27, Eq. (07.34.03.0046.01)] can rewrite (24) as:

$$p_2 = 1 - G_{0,1}^{1,0}\left[\frac{\gamma_{th}}{\mu_2 \sigma_{SD}^2}\Big|_{0}^{-}\right] \tag{25}$$

Now with $p_1$ and $p_2$ in our hands, we can extract the outage probability of the system.

## 4. NUMERICAL RESULTS

In this section, some numerical results based on Monte-Carlo simulations are presented to verify the theoretical analysis derived in the previous section. Two different turbulence conditions for the FSO link is assumed, one is strong condition with following parameters: $\alpha = 0.5$, $\beta = 1.8$. Another one is moderate condition with following parameters: $\alpha = 0.55$, $\beta = 2.35$ [29]. The rytov variance for these two cases are 25 and 2, respectively. It is illustrated in [19] that as the value of $\boldsymbol{\xi}$ increases, the effect of pointing error decreases. Therefore we assume two different values $\xi = 1.09$ and $\xi = 7.35$ such as in [7] to see the effect of pointing error.

Fig. 3 shows the outage probability versus the average SNR of the FSO link. The analytical expressions are based on (15) which correspond to the outage probability of the system. In this example, we consider moderate turbulence conditions, and $\xi = 7.35$. It is observed from figure that the simulation result is very close to the derived expressions in (15) indicating its accuracy.

Fig. 4 expresses the outage probability performance of the system given in (15) for the two different turbulences conditions and pointing errors ($\xi = 1.09$ and $\xi = 7.35$ are corresponding to large and small pointing errors respectively). As observed, the outage performance degrades as the atmospheric turbulence condition and pointing error deteriorate.

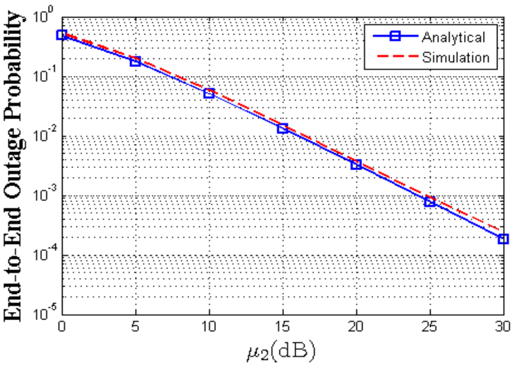

**Fig. 3.** Outage probability versus the average SNR of the FSO link, moderate turbulence regime.

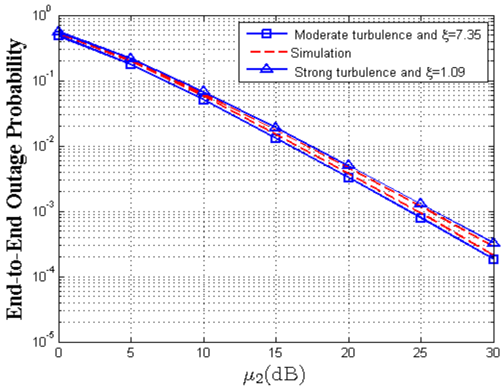

**Fig. 4.** Outage probability for different turbulence conditions and ξ.

Fig. 5 shows the average throughput of the system versus the energy harvesting parameter $\tau$ for the case of strong turbulence regime and assuming $\mu_2 = 20\,dB$ and $\xi = 1.09$. The diagrams are plotted for two different qualities of the R-D link. It is observed from the figure that as the quality gets better (the parameter $\sigma_{\mathrm{RD}}^2$ becomes larger), the parameter $\tau$ gets smaller; because the power needed for forwarding information to the destination is lower and therefore the time for energy harvesting is lower. The delay-sensitive throughput is defined as $\frac{\mathrm{R}}{2}(1-\tau)(1-\mathrm{P}_{\mathrm{out}}(\gamma_{\mathrm{th}}))$ where $R = \log_2(1+\gamma_{th})$ [31]. As can be seen, for this scenario, there exist an optimum $\tau$ that results in the maximum throughput.

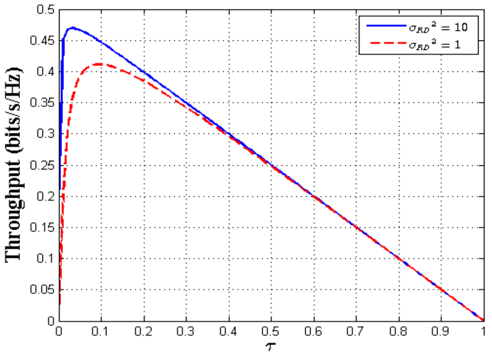

**Fig. 5**. Average throughput of the system versus the energy harvesting parameter τ for two different qualities of the R-D link.

## 5. CONCLUSION

In this paper we have introduced a system model for energy harvesting in a mixed FSO-RF system in downlink transformation. The relay harvests energy from the source and uses it to forward information to the destination. The FSO link experiences Gamma-Gamma atmospheric turbulence conditions, while the RF links are subjected to Rayleigh fading. AF relaying for cooperating was assumed. The closed-form expression for the outage probability is derived and the result is verified by Monte-Carlo simulation.

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