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A novel hybrid FSO / RF communication system with receive diversity

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ABSTRACT

This paper presents a novel model for hybrid Free Space Optical / Radio Frequency (FSO / RF) communication system with receive diversity. It is the first time that in a one-hop hybrid FSO / RF system, receive diversity is being used. Also, it is the first time that a one-hop hybrid FSO / RF system is being investigated in Negative Exponential atmospheric turbulence. For the first time, closed-form expression for Outage Probability of the presented system is being derived and verified through MATLAB simulation. It is shown that at low average Signal to Noise Ratio (SNR), FSO system with receive diversity performs better than RF system with receive diversity and almost equal to the proposed system, but by the increase of average SNR, its performance degrades compared with the two other systems. This system has a complex receiver, but it should be noted that the addition of this complexity, significantly reduces power consumption and improves system performance.

1. Introduction

Over the last decades, need to high data rates led to more attention to FSO systems and made them the main competitor of traditional communication systems. RF system is appropriate in term of cost but provides lower data rate compared with FSO. FSO system provides both low cost and high data rate [1].

Some atmospheric turbulences such as fog degrades FSO systems, therefore FSO is not reliable. A solution to this problem is to combine FSO and RF links. Millimeter wave RF systems, achieve data rates equal with FSO systems. Impact of weather condition on FSO and RF links is not the same [2], for example in FSO links performance degradation is mostly because of fog, atmospheric turbulences but heavy rain doesn't affect it. In contrast, RF is sensitive to heavy rain but does not care fog and atmospheric turbulences [3].

Receive diversity is a way of improving performance of communication systems. In this technique, different copies of the original signal, are encountered with different fading. By combining these copies, receivers can recover the original data better [4].

Serial and parallel structures have been proposed for data transmission in hybrid FSO / RF systems. In the parallel structure, data is transmitted through two parallel FSO and RF links. In this structure, FSO link is always active. When the received SNR comes down below a threshold, RF link begins transmitting data. This technique is called soft switching [5,6]. This technique suffers from continues switches when weather conditions get worst. One solution for this problem is simultaneous transmission, in which both FSO and RF links are always active. In soft switching, RF receiver notifies transmitter through a feedback link, but simultaneous transmission requires no feedback. Maximum Ratio Combiner (MRC), Equal Gain Combiner (EGC) and Selection Combiner (SC) are some

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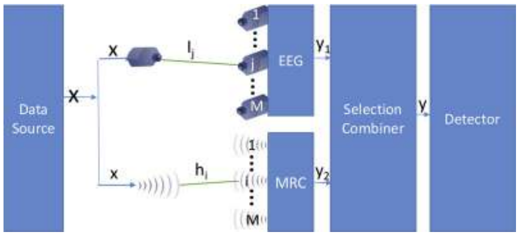

Fig. 1. The proposed hybrid FSO / RF communication system.

ways of extracting original data form different received copies of data [7,8].

This paper presents a novel model for hybrid FSO/RF system. To the best of author's knowledge, it is the first time in a hybrid FSO / RF system, receive diversity is used. In FSO link EGC is used because no closed-form expression can be derived for the probability distribution function (pdf) and Cumulative Density Function (CDF) of MRC scheme in an FSO link with receive diversity in Negative Exponential distribution. In RF link MRC is used because as mentioned in [9], the pdf and CDF of SNR at EGC input at Rayleigh distribution do not exist in closed-form. Multiple receiver structure of this system helps the receiver to make a better decision by combining several copies of the original signal encountered with different atmospheric turbulence, and therefore substantially improves system performance. On the other hand combination of FSO and RF systems brings advantages of both FSO and RF systems.

In system considered in Fig. 1, RF link has Rayleigh fading and FSO link has Negative Exponential atmospheric turbulence. In FSO system, Intensity Modulation and Direct Detection (IM/DD) is used. The rest of the paper is organized as follows: section II describes the system model. Section III derives pdf of the presented structure, section IV derives Outage Probability of the presented system. Section V compares analytical and simulation results. Section VI is conclusion of this study.

2. System model

As shown in Fig. 1, two copies of signal are simultaneously transmitted through parallel FSO and RF links. These signals encounter with the effects of FSO and RF channels and at the receiver, noise is added to the signals. MRC at the RF receiver and EGC at the FSO receiver combine different collected copies of the original signal. Then between output signals of MRC and EGC, with maximum SNR is selected by the SC and is used for detection. It is assumed that FSO and RF links have the same number of receivers.

SNR at the input of each of MRC and EGC combiners, and thus SNR at the input of SC combiner, is calculated in this section.

2.1. FSO link

The pdf of Negative Exponential atmospheric turbulence is as follows [9]:

$$f_{I_i}(z) = \lambda e^{-\lambda z} \tag{1}$$

where I_i, the intensity of $i-th\,;\, i = 1,2, \ldots, M$ FSO path, has Negative Exponential distribution with $1/\lambda$ mean and $1/\lambda^2$ variance. Assuming x as the transmitted signal, received signal at $i-th$ FSO receiver, is $y_i = \eta I_i x + e_i$; where η is the optical to electrical conversion efficiency and e_i, the input noise of i^{th} FSO receiver, is Additive White Gaussian Noise (AWGN) with zero mean and σ^2 variance. The output of EGC combiner is as follows:

$$y_1 = \sum\nolimits_{i=1}^{M} y_i = \eta \sum\nolimits_{i=1}^{M} I_i x + \sum\nolimits_{i=1}^{M} e_i \tag{2}$$

Therefore, SNR at the output of EGC is as follows:

$$\gamma_1 = \frac{\eta^2 E[x^2] \left(\sum_{i=1}^{M} I_i\right)^2}{M\sigma^2} = \frac{\bar{\gamma}_1}{M}\left(\sum\nolimits_{i=1}^{M} I_i\right)^2$$

where M is number of FSO receiver. $\bar{\gamma}_1 = \eta^2 E[x^2]/\sigma^2$ is average SNR at input of EGC and $E[x^2]$ is transmitted signal energy.

2.2. RF link

The pdf of i^{th}; $i = 1,2, \ldots, M$ RF path is as follows [9]:

$$f_{|h_i|}(z) = \frac{z}{\sigma_r^2} e^{-\frac{z^2}{2\sigma_r^2}} \tag{3}$$

where $h_i = r_i e^{j\theta_i}$ is fading coefficient of i^{th} RF path. Assuming $y_i = h_i x + e_i$ as the received signal at i^{th} RF receiver, e_i is RF receiver input noise with σ^2 variance. MRC output is a weighted sum ratio of its input signals. This weight is selected to eliminate the effect of the signal phase and amplifies the signal.

SNR at each branch of MRC is calculated as follows:

$$\gamma_i = \frac{E[|h_i x|^2]}{\sigma^2} = \frac{E[x^2] r_i^2}{\sigma^2} = \bar{\gamma}_i r_i^2, \tag{4}$$

where $\bar{\gamma}_i = E[x^2]/\sigma^2$ is average SNR at the input of i^{th} RF receiver. SNR at the output of MRC is as follows [9]:

$$\gamma_2 = \frac{E[x^2]\sum_{i=1}^{M} r_i^2}{\sigma^2} = \sum_{i=1}^{M} \gamma_i, \tag{5}$$

where M is number of RF receivers.

3. Probability density function

3.1. FSO link

Moment Generating Function (MGF) of i^{th} FSO path is as follows:

$$M_{I_i}(s) = \int_0^\infty \lambda e^{-\lambda z} e^{-sz} dz = \frac{\lambda}{s+\lambda}. \tag{6}$$

Assuming independent FSO links achieves [11]:

$$M_{\sum_{i=1}^{M} I_i}(s) = (M_{I_i}(s))^M = \left(\frac{\lambda}{s+\lambda}\right)^M. \tag{7}$$

Inverse Laplace transform of MGF is equal to:

$$f_{\sum_{i=1}^{M} I_i}(z) = L^{-1}\left(M_{\sum_{i=1}^{M} I_i}(s)\right) = \lambda^M \frac{z^{M-1}}{\Gamma(M)} e^{-\lambda z}. \tag{8}$$

Using (9) and [10, Eq. 5.4] achieves:

$$f_{\left(\sum_{i=1}^{M} I_i\right)^2}(v) = \frac{\lambda^M}{2\Gamma(M)} v^{\frac{M}{2}-1} e^{-\lambda\sqrt{v}}. \tag{9}$$

Using [10, Eq. 5.18] and (10) the pdf of γ_1 random variable is equal to:

$$f_{\gamma_1}(\gamma) = \frac{\lambda^M}{2\Gamma(M)\left(\frac{\bar{\gamma}_1}{M}\right)^{\frac{M}{2}}} \gamma^{\frac{M}{2}-1} e^{-\lambda\sqrt{\frac{\gamma}{\left(\frac{\bar{\gamma}_1}{M}\right)}}} \tag{10}$$

3.2. RF link

The pdf of i^{th} RF path is as follows:

$$f_i(\gamma) = \frac{1}{\bar{\gamma}_2} e^{-\frac{\gamma}{\bar{\gamma}_2}}. \tag{11}$$

MGF of i^{th} RF path becomes equal to:

$$M_{\gamma_i}(s) = \int_0^\infty \frac{1}{\bar{\gamma}_2} e^{-\frac{\gamma}{\bar{\gamma}_2}} e^{-s\gamma} d\gamma = \frac{\frac{1}{\bar{\gamma}_2}}{s + \frac{1}{\bar{\gamma}_2}}. \tag{12}$$

Assuming independence of RF path fading achieves [11]:

$$M_{\sum_{i=1}^{M} \gamma_i}(s) = (M_{\gamma_i}(s))^M = \frac{\frac{1}{\bar{\gamma}_2^M}}{\left(s + \frac{1}{\bar{\gamma}_2}\right)^M}. \tag{13}$$

Taking inverse Laplace transform of above function, pdf of γ_2 random variable becomes equal to:

$$f_{\gamma_2}(\gamma) = L^{-1}\left(M_{\sum_{i=1}^{M} \gamma_i}(s)\right) = \frac{\gamma^{M-1} e^{-\frac{\gamma}{\bar{\gamma}_2}}}{\bar{\gamma}_2^M \Gamma(M)}. \tag{14}$$

4. Outage probability

In this section, closed-form expressions are derived for Outage Probability. The outage occurs in a system when the input SNR comes down below a threshold, i.e. $\gamma \leq \gamma_{th}$. According to this definition, Outage Probability is equal to:

$$P_{out}(\gamma_{th}) = \Pr(\gamma \leq \gamma_{th}). \tag{15}$$

However, as described in Fig. 1, between output signals of MRC and EGC, signal with maximum SNR is selected by SC combiner, namely:

$$\gamma = \max(\gamma_1, \gamma_2). \tag{16}$$

Therefore, assuming independent FSO and RF links, (16) comes in as follows:

$$P_{out}(\gamma_{th}) = \Pr(\gamma \leq \gamma_{th}) = \Pr(\max(\gamma_1, \gamma_2) \leq \gamma_{th}) = \Pr(\gamma_1 \leq \gamma_{th}, \gamma_2 \leq \gamma_{th}) = P_{out}(\gamma_1 \leq \gamma_{th}) P_{out}(\gamma_2 \leq \gamma_{th}). \tag{17}$$

By calculation the individual Outage Probability of FSO and RF links and multiplication of them, Outage Probability of the presented system is calculated.

4.1. FSO link

By integration of (11) the Outage Probability of FSO link becomes as follows:

$$P_{out_{\gamma_1}}(\gamma_{th}) = \int_0^{\gamma_{th}} \frac{\lambda^M}{2\Gamma(M)\left(\frac{\bar{\gamma}_1}{M}\right)^{\frac{M}{2}}} \gamma^{\frac{M}{2}-1} e^{-\lambda\sqrt{\frac{\gamma}{\left(\frac{\bar{\gamma}_1}{M}\right)}}} d\gamma. \tag{18}$$

Substituting equivalent Meijer-G form of $e^{-\lambda\sqrt{\gamma/(\bar{\gamma}_1/M)}}$ as $\frac{1}{\sqrt{\pi}} G_{0,2}^{2,0}\left(\frac{\lambda^2\gamma}{4\bar{\gamma}_1/M}\middle|\begin{smallmatrix}-\\0,0.5\end{smallmatrix}\right)$ [12, Eq.07.34.03.1081.01], the above integral becomes as follows:

$$P_{out_{\gamma_1}}(\gamma_{th}) = \frac{\lambda^M}{2\sqrt{\pi}\Gamma(M)\left(\frac{\bar{\gamma}_1}{M}\right)^{\frac{M}{2}}} \int_0^{\gamma_{th}} \gamma^{\frac{M}{2}-1} G_{0,2}^{2,0}\left(\frac{\lambda^2\gamma}{\frac{4\bar{\gamma}_1}{M}}, \begin{matrix}-\\0,0.5\end{matrix}\right) d\gamma. \tag{19}$$

Using [12, Eq. 07.34.21.0084.01], Outage Probability of FSO link is equal to:

$$P_{out_{\gamma_1}}(\gamma_{th}) = \frac{\lambda^M}{2\sqrt{\pi}\Gamma(M)\left(\frac{\bar{\gamma}_1}{M}\right)^{\frac{M}{2}}} \gamma_{th}^{\frac{M}{2}} G_{1,3}^{2,1}\left(\frac{\lambda^2\gamma_{th}}{\frac{4\bar{\gamma}_1}{M}}, \begin{matrix}1-\frac{M}{2}\\0,0.5,-\frac{M}{2}\end{matrix}\right) \tag{20}$$

4.2. RF link

By integration of (15), Outage Probability of RF link becomes as follows:

$$P_{out_{\gamma_2}}(\gamma_{th}) = \int_0^{\gamma_{th}} \frac{\gamma^{M-1} e^{-\frac{\gamma}{\bar{\gamma}_2}}}{\bar{\gamma}_2^M \Gamma(M)} d\gamma = 1 - e^{-\frac{\gamma_{th}}{\bar{\gamma}_2}} \sum_{k=1}^{M} \frac{\left(\frac{\gamma_{th}}{\bar{\gamma}_2}\right)^{k-1}}{\Gamma(k)}. \tag{21}$$

where the following equation is used to calculate the above integral [13, Eq.01.03.21.0059.01]:

$$\int z^n e^{az} d\gamma = = -(-a)^{-n-1} n! e^{az} \sum_{k=0}^{n} \frac{(-az)^k}{k!}/; \tag{22}$$

From (18), (21) and (22), Outage Probability of the presented system obtains as follows:

$$P_{out}(\gamma_{th}) = \left(1 - e^{-\frac{\gamma_{th}}{\bar{\gamma}_2}} \sum_{k=1}^{M} \frac{\left(\frac{\gamma_{th}}{\bar{\gamma}_2}\right)^{k-1}}{\Gamma(k)}\right) \times \left(\frac{\lambda^M}{2\sqrt{\pi}\Gamma(M)\left(\frac{\bar{\gamma}_1}{M}\right)^{\frac{M}{2}}} \gamma_{th}^{\frac{M}{2}} G_{1,3}^{2,1}\left(\frac{\lambda^2\gamma_{th}}{\frac{4\bar{\gamma}_1}{M}}, \begin{matrix}1-\frac{M}{2}\\0,0.5,-\frac{M}{2}\end{matrix}\right)\right). \tag{23}$$

5. Simulation results

This section evaluates performance of presented hybrid FSO / RF system for different variances of Negative Exponential atmospheric turbulence as well as for different number of receivers. The proposed structure is also compared with common FSO and RF systems with receive diversity. FSO and RF receiver inputs are assumed to have equal average SNR ($\bar{\gamma}_1 = \bar{\gamma}_2 = \gamma_{avg}$).

In Fig. 2, Outage Probability of the presented hybrid FSO / RF system is plotted in terms of average SNR for different number of receivers for unit variance of Negative Exponential atmospheric turbulence and $\gamma_{th} = 10dB$. As can be seen at $P_{out} = 10^{-5}$, there is about $8dB$ difference in γ_{avg} between cases of M = 1 and M = 2, thereby addition of only one receiver significantly decreases power consumption, hence proposed system is suitable for situations in which power consumption is the major challenge in communication.

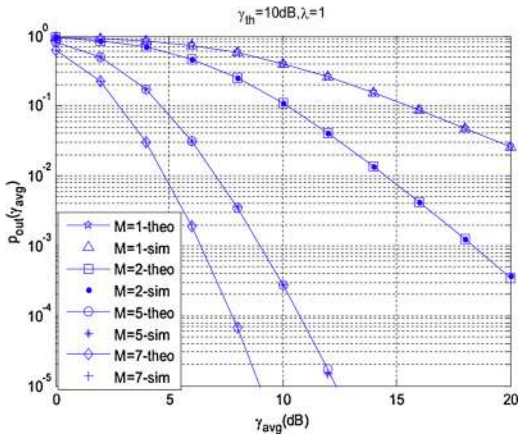

Fig. 2. Outage Probability of the presented hybrid FSO / RF system in terms of average SNR for different number of receivers for unit variance of Negative Exponential atmospheric turbulence and $\gamma_{th} = 10dB$.

Power consumption is a major problem especially in saturated atmospheric turbulence regimes, because this kind of turbulence usually occurs at bad weather climates such as seas, in which providing the required power for communication is the major problem, and a system with low power consumption is suitable for this conditions.

Fig. 3 compares Outage Probability of the presented hybrid FSO / RF system with receive diversity in terms of average SNR, for different atmospheric turbulence variances when number of receiver is M = 2 and $\gamma_{th} = 10dB$. As can be seen, at $P_{out} = 10^{-3}$, there is about $5dB$ between two cases of $\lambda = 0.5$ and $\lambda = 1$, hence a small change in atmospheric turbulence, significantly changes system performance.

In this paper, also performance of common FSO and RF systems with receive diversity is compared with proposed hybrid FSO / RF system. In Fig. 4, Outage Probability of common FSO and RF systems, compared with presented FSO / RF system is plotted in terms of average SNR. As can be seen, at low γ_{avg}, Outage Probability of FSO link is less than RF link and almost equal with proposed hybrid FSO / RF links, but by increase of γ_{avg}, its performance degrades. At all shown γ_{avg}, presented FSO / RF system performs better than the two others. This is related to Rayleigh and Negative Exponential distributions, because peak of Negative Exponential pdf is at low SNRs while peak of Rayleigh pdf is in higher SNRs it means that loss of Negative Exponential atmospheric turbulence is higher at high SNRs.

6. Conclusion

In this paper, a novel model for hybrid FSO / RF system with receive diversity is presented. In which for the first time receive diversity is used in a one-hop hybrid FSO / RF system. FSO link is modeled by Negative Exponential distribution and RF link is modeled by Rayleigh distribution. Outage Probability of the presented system is evaluated in different atmospheric turbulence variances and different number of receivers. Also the, proposed system is compared with common FSO and RF systems with receive diversity. The presented system is recommended to use especially in a Mediterranean climate where one of the FSO and RF links is always in outage due to heavy rain or dense fog. Although the proposed received diversity has more complexity, it should be noted

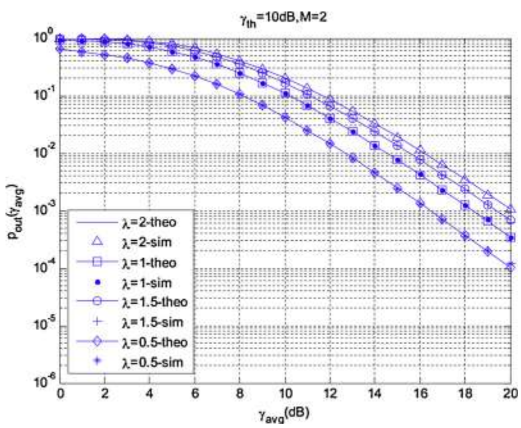

Fig. 3. Outage Probability of the presented hybrid FSO / RF system with receive diversity in terms of average SNR, for different atmospheric turbulence variances when number of receiver is M = 2 and $\gamma_{th} = 10dB$.

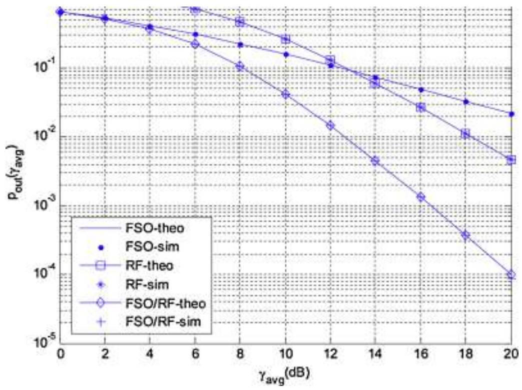

Fig. 4. Outage Probability of common FSO and RF systems with receive diversity, and proposed hybrid FSO / RF system, in terms of average SNR when $M = 2$, $\lambda = 0.5$ and $\gamma_{th} = 10dB$.

that addition of this complexity, significantly reduces power consumption and improves performance of the system.

References

[1] A. Douik, H. Dahrouj, T.Y. Al-Naffouri, M.S. Alouini, Hybrid radio / free-space optical design for next generation backhaul systems, IEEE Trans. Commun. 64 (June 6) (2016).
[2] L. Chen, W. Wang, C. Zhang, Multiuser diversity over parallel and hybrid FSO / RF links and its performance analysis, IEEE Photonics J. 8 (June 3) (2016).
[3] V.V. Mai, A.T. Pham, Adaptive multi-rate designs and analysis for hybrid FSO / RF systems over fading channels, Ieice Trans. Commun. e98-B (July 8) (2015) 1660–1671.
[4] F. Nadeem, V. Kvicera, M.S. Awan, E. Leitgeb, S.S. Muhammad, G. Kandus, Weather effects on hybrid FSO / RF communication link, IEEE J. Sel. Areas Commun. 27 (December 9) (2009).
[5] H. Kazemi, M. Uysal, F. Touati, Outage analysis of hybrid FSO / RF systems based on finite-state Markov chain modeling, 3rd International Workshop in Optical Wireless Communications (Iwow), (2014) Sept.
[6] Y. Zhang, Y. Park, B.Y. Kim, K.D. Kim, Performance analysis of hybrid FSO / RF system, Third International Conference on Ubiquitous and Future Networks (Icufn), (2011) Jun.
[7] I.E. Lee, Z. Ghassemlooy, W.P. Ng, S. Rajbhandari, Fundamental Analysis of Hybrid Free Space Optical and Radio Frequency Communication Systems, (2011).
[8] N.D. Chatzidiamantis, G.K. Karagiannidis, E.E. Kriezis, M. Matthaiou, Diversity combining in hybrid RF / FSO with PSK modulation systems, 2011 IEEE International Conference on Communications (ICC) 5-9 (2011) Jun.
[9] A. Goldsmith, Wireless Communications, University Press Cambridge, 2004.
[10] A. Papoulis, S.U. Pillai, Probability, Random Variables, and Stochastic Presses, 4th edition, McGraw-Hill, 2002, p. 162.
[11] M.R. Bhatnagar, S. Anees, On the performance of alamouti scheme in fading gamma-gamma FSO links with pointing errors, IEEE Wirel. Commun. Lett. 4 (February 1) (2015).
[12] Http://Functions.wolfram.com/Hypergeometricfunctions/.
[13] http://functions.wolfram.com/ElementaryFunctions/Exp/.