**FACTA UNIVERSITATIS**
Series: **Automatic Control and Robotics** Vol. 14, N° 3, 2015, pp. 205 - 217

# OUTAGE PERFORMANCE OF COGNITIVE RF/FSO SYSTEM WITH MRC SCHEME AT THE RECEIVER

*UDC (621.391+621.395.38):519.7)*

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**Abstract**. *The aim of this paper is performance analysis of the hybrid radio frequency (RF)/free-space optical (FSO) system, where the transmission is performed simultaneously over FSO link and spectrum sharing cognitive RF sub-system. The FSO link is affected by Gamma-Gamma atmospheric turbulence, while in spectrum sharing cognitive RF sub-system the peak interference power constraint at the primary user's receiver is considered in Nakagami-m fading environment. Outage probability expressions are provided in the integral form for the case when the maximal ratio combining (MRC) is applied at the destination. The effects of the atmospheric turbulence strength, the number of RF antennas, allowable power and fading severity on the outage performance are observed. Numerical results are presented and verified by Monte Carlo simulations.*

**Key words**: *cognitive radio, free-space optical communications, interference power constraint, Nakagami-m fading, outage probability, spectrum sharing communications.*

## 1. INTRODUCTION

Free-space optical (FSO) systems have become very important since they enable more economical optical signal transmission in regard to fiber optics, proving savings in time and money [1]. Furthermore, the FSO system implementation has a number of advantages over radio frequency (RF) systems because they use unlicensed and wider bandwidth, providing high transmission speeds and supporting a larger number of users. Also, these systems are characterized by the absence of interference, easy and quick implementation,

Received October 26, 2015
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being a suitable solution for the “last mile” problem [1]. In addition to the offered aforementioned advantages, the use of FSO systems is limited by the presence of atmospheric turbulence, which occurs as a result of random changes in refractive index caused by variations in atmospheric pressure, temperature and altitude. One of the statistical models proposed to describe the intensity fluctuations, which are result of the atmospheric turbulence phenomenon, is a Gamma-Gamma model suitable in a wide range of conditions of turbulence [1].

The atmosphere and weather conditions differently affect the quality of the wireless signal in RF and FSO transmission. For example, fog degrades the FSO link performance to a large extent, until rain has a negligible effect on signal transmission over FSO channels. On the other hand, heavy rain has an impact on the RF signal transmission, while the influence of fog is small and negligible [2]–[3]. The idea of the hybrid system deployment comes from the fact that RF and FSO are both the wireless technologies, but weather conditions differently affect the quality of corresponding signal transmission. To obtain better system performance, the hybrid RF/FSO systems have been proposed in the literature [4]–[5]. In [4], by using the experimental measurements, the authors proved that hybrid system with RF and FSO channels significantly increase availability compared to the FSO system only. The average bit error rate (BER) performance of hybrid RF/FSO system employing maximal ratio combining (MRC) and selection combining (SC) diversity at the receiver are derived in [5].

The performance improvement can be also achieved by introducing the relay technologies, which provide the line-of-sight and the FSO link deployment [6]. The first hop is usually RF link, while the second hop represents FSO signal transmission. The analysis of the RF/FSO system performance with amplify-and-forward (AF) relay has been extended through the papers [7]–[10]. Further improvement of the system performance can be accomplished by the hybrid RF and RF/FSO systems, which besides the RF/FSO relay links have direct RF link [11]. Assuming the fading over RF link is modeled by Rayleigh distribution and the FSO link is described by the combined model that considers Gamma-Gamma atmospheric turbulence and pointing errors, the performance analysis of the hybrid RF and RF/FSO systems were presented in [11]–[12]. Outage performance of such system where RF links are modeled by Nakagami-*m* distribution is analyzed in [13].

On the other hand, cognitive radio is proposed as effective solution for overcoming the problem of the lack of available spectrum bands [14]. Although the various concepts of cognitive radio communications exists [15], spectrum sharing has advantage of simultaneous using the spectrum with the licensed (primary) user. In this concept cognitive user is allowed to transmit as long as the interference it causes at the input of the primary receiver is lower than the permitted threshold [16]. In order to fulfill these requirements, transmit power of the cognitive user is adapted to the conditions in the propagation environment [17], which further limits spectrum sharing system performances. The improvement of system capacity by employing MRC at the cognitive receiver is proposed in [18]. The performances of spectrum sharing system with MRC are analyzed in [19] for the case of Rayleigh fading, while the capacity analysis is provided in [20] for Nakagami-*m* propagation environment.

The use of combined RF/FSO system in which the RF part includes cognitive radio transmission is proposed in [21]–[22]. The authors analyzed asymmetric mixed RF/FSO dual-hop transmission system, where first section power control is applied to maintain the interference at the primary network within a predetermined threshold (i.e., the spectrum sharing cognitive radio transmission) and the second link is trailed by FSO technology.

In this paper we analyze the performance of a hybrid RF/FSO system, where the license-free communication is provided by the FSO sub-system, while the RF sub-system is employed as the back-up link. In the RF domain, user is allowed to maintain spectrum sharing communications under peak interference power constraint. It is also assumed that maximal transmit power of RF transmitter is limited. Unlike [21]–[22] signal transmission is performed simultaneously via the FSO link and cognitive spectrum sharing RF system, when the MRC signal combining at the destination is applied. Outage probability expression is derived and the effects of the power limitations and atmospheric turbulence parameters on system performance are analyzed. The numerical results are confirmed by Monte Carlo simulations.

## 2. System and Channel Model

The system consists of the FSO and the cognitive RF sub-systems. In the FSO part of the system, signal transmission is performed through the channel influenced by atmospheric turbulence. Since the FSO link performance is heavily dependent on certain weather conditions (e.g. fog), the RF sub-system is used as the back up link. The user in the RF domain shares spectrum licensed to the primary user, so the signal transmission is performed with certain restrictions. The peak interference power constraint is assumed in the considered RF sub-system scenario. The receiver is equipped with multiple RF antennas and the optical detector which converts the optical signal into an electrical one. The MRC diversity is applied at the receiver to perform signal combining.

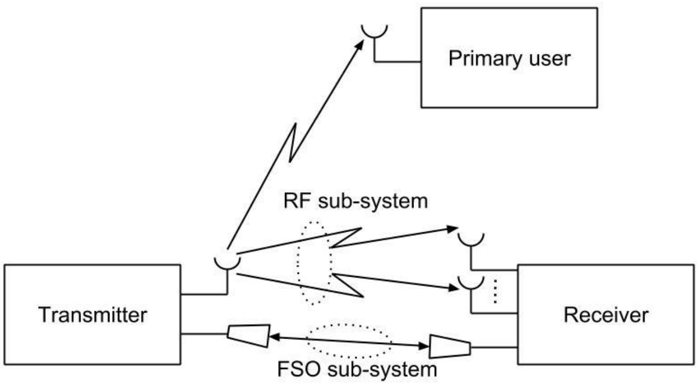


**Fig. 1** Hybrid cognitive RF/FSO system model

As shown in Fig. 1, the signal from the transmitter to the receiver is carried over two parallel channels, i.e. FSO and RF sub-systems. The FSO sub-system consists of single FSO link. On the other hand, in the RF sub-system it is assumed that transmitter shares the spectrum with the primary user under the assumption of the peak interference power constraint and the maximal allowable power.

**2.1. FSO sub-system**

The FSO sub-system consists of transmitting aperture and receiver detector, which employs intensity modulation and direct detection (IM/DD) with On-Off (OOK) scheme. The simplicity of OOK scheme reflects in the fact that the optical source (laser) is active only when the bit "*on*" is transmitted. At the transmitting part of the FSO sub-system, signal bearing information is intensity modulated by electro-optical modulator IM/OOK. The size and direction of the optical beam are determined by laser source within the transmitting telescope, which sends optical beam to the receiver via atmospheric turbulence-induced channel. If the average transmitted optical power is denoted by $P_t$, the signal intensity at the transmitter output is $2P_t$ when transmitted bit is "*on*", and 0 when transmitted bit is "*off*". The FSO link is impaired by the atmospheric turbulence which causes the intensity fluctuations at the received signal. At the destination, direct detection is performed and the optical signal is converted to the electrical one by PIN photodetector with a conversion coefficient $\eta$. The received electrical signal is given in the form [23]

$$y = x\eta I + n\,, \tag{1}$$

where $x \in \{0,2P_t\}$, $n$ is the additive white Gaussian noise (AWGN) with the zero-mean and variance $\sigma_n^2$ and $I$ is the fading amplitude over the FSO link which originates from the atmospheric turbulence. Another method for converting an optical signal into an electrical one can be performed by avalanche photodiode (APD) [24].

Based on (1), the instantaneous SNR is defined as

$$\gamma_{FSO} = \frac{2{P_t}^2\eta^2}{\sigma_n^2} I^2\,, \tag{2}$$

and the average SNR is determined as [25]

$$\bar{\gamma}_{FSO} = \mathrm{E}[\gamma_{FSO}] = \frac{2P_t^2\eta^2}{\sigma_n^2}\mathrm{E}[I^2]\,, \tag{3}$$

where E[·] denotes the statistical expectation. The alternative SNR definition usually used in FSO literature is the average electrical SNR. Since $I$ is normalized, it holds $\mathrm{E}[I] = 1$, so the electrical average SNR is given by [25]

$$\mu_{FSO} = \frac{2{P_t}^2\eta^2}{\sigma_n^2}\mathrm{E}^2[I] = \frac{2{P_t}^2\eta^2}{\sigma_n^2}\,. \tag{4}$$

The FSO sub-system is under the influence of atmospheric turbulence which causes the intensity fluctuations at the received signal modeled by Gamma-Gamma distribution. The instantaneous SNR, $\gamma_{\mathrm{FSO}}$, has the probability density function (PDF) given by [6]

$$f_{\gamma_{FSO}}(\gamma) = \frac{(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)\mu_{FSO}^{(\alpha+\beta)/4}}\gamma^{(\alpha+\beta)/4-1}K_{\alpha-\beta}\left(2\sqrt{\alpha\beta\sqrt{\frac{\gamma}{\mu_{FSO}}}}\right), \tag{5}$$

where $K_v(\cdot)$ is the $v$-th order modified Bessel function of the second kind [26, eq. (8.432.2)].

The parameters $\alpha$ and $\beta$ are the atmospheric turbulence parameters related to the atmospheric conditions trough the Rytov variance $\sigma_R^2$. The plane wave propagation and zero inner scale are considered, so the parameters $\alpha$ and $\beta$ are found as [1], [24]

$$\alpha = \left( \exp\left[ \frac{0.49\sigma_R^2}{(1+1.11\sigma_R^{12/5})^{7/6}} \right] - 1 \right)^{-1},$$
$$\beta = \left( \exp\left[ \frac{0.51\sigma_R^2}{(1+0.69\sigma_R^{12/5})^{5/6}} \right] - 1 \right)^{-1}, \tag{6}$$

where the Rytov variance $\sigma_R^2$ is used as a metric of the turbulence strength.

The cumulative distribution function (CDF) is given by [5]

$$F_{\gamma_{FSO}}(\gamma) = \int_0^{\gamma} f_{FSO}(u)du = \frac{1}{\Gamma(\alpha)\Gamma(\beta)} G_{1,3}^{2,1}\left( \alpha\beta\sqrt{\frac{\gamma}{\mu_{FSO}}} \middle| \begin{matrix} 1 \\ \alpha, \quad \beta, \quad 0 \end{matrix} \right). \tag{7}$$

### 2.2. Cognitive RF sub-system

We consider the RF sub-system where transmitter shares the spectrum with the primary user, under the constraint that peak interference power that secondary user causes at the primary user's receiver cannot exceed predefined threshold $Q_p$. Also, we assume that the maximal transmit power of the secondary transmitter is limited and equal $P_m$. Furthermore, in RF domain, the receiver is equipped with $n_R$ receive antennas and applies MRC to signals from all $n_R$ antennas.

Fading envelopes $h_i$, $i$=1, ..., $n_R$ are assumed to be independent and identically distributed (i.i.d) random variables (RVs), following the Nakagami-*m* distribution, with fading parameter at the secondary link equal $m_{Si}=m_S$, $i$=1, ..., $n_R$ and normalized mean square value $\lambda_S = E[h_i^2]/m_S$ $i$ =1, ..., $n_R$. The corresponding PDF is given with [27]

$$f_h(h) = \frac{2h^{2m_S-1}}{\lambda_S^{m_S}(m_S-1)!} e^{-\frac{h^2}{\lambda_S}}. \tag{8}$$

Fading envelope, $g$, in the link from the secondary transmitter to the primary receiver also follows the Nakagami-*m* distribution, with the fading parameters equal $m_p$, $\lambda_p = E[g^2]/m_p$ and the following PDF expression

$$f_g(g) = \frac{2g^{2m_P-1}}{\lambda_P^{m_S}(m_P-1)!} e^{-\frac{g^2}{\lambda_P}}. \tag{9}$$

The channel power gain of the secondary link between the transmitter and the MRC receiver is denoted by $a = \sum_{i=1}^{n_R} |h_i|^2$ and follows Gamma distribution, with the corresponding PDF [27]

$$f_a(a) = \frac{a^{m_S n_R - 1}}{\lambda_S^{m_S}(m_S n_R - 1)!} e^{-\frac{a}{\lambda_S}}. \tag{10}$$

Similarly, the channel power gain of the link from the secondary transmitter to the primary receiver is denotes by $b = |g|^2$ and it is distributed according to following PDF

$$f_b(b) = \frac{b^{m_P - 1}}{\lambda_P^{m_P}(m_P - 1)!} e^{-\frac{b}{\lambda_P}} . \tag{11}$$

The secondary transmitter applies power adaptation to fulfill the condition that the interference power at the primary receiver is lower than threshold $Q_p$, and the transmit power of the secondary user $P_{SU\text{-}Tx}$ should satisfy

$$bP_{SU-Tx} \le Q_p . \tag{12}$$

In the considered scenario the maximal emitted transmit power of secondary user is also limited and equal $P_m$. Therefore, the RF transmit power is given by

$$P_{SU-Tx} = \begin{cases} P_{m,} & b \le \dfrac{Q_p}{P_m}, \\ \dfrac{Q_p}{b}, & b > \dfrac{Q_p}{P_m}. \end{cases} \tag{13}$$

The resultant SNR at the output of the RF receiver $\gamma_{RF}$ is equal

$$\gamma_{RF} = \begin{cases} a\dfrac{P_{m,}}{\sigma^2}, & b \le \dfrac{Q_p}{P_m}, \\ \dfrac{a}{b}\dfrac{Q_p}{\sigma^2}, & b > \dfrac{Q_p}{P_m}. \end{cases} \tag{14}$$

where $\sigma^2$ denotes the noise at the input to the secondary user's receiver.
Using the transformations of R.Vs. and solving integrals as in [28, eqs. (8) - (10)], the PDF of R.V. $\gamma_{RF}$ is given by

$$\begin{aligned} f_{\gamma_{RF}}(u) = {} & \frac{u^{m_S n_R - 1} \; e^{-\frac{u}{P_m \lambda_S/\sigma^2}}}{(P_m\lambda_S/\sigma^2)^{m_S n_R} \lambda_P^{m_P} (m_S n_R - 1)\;!} \times \left(1 - e^{-\frac{Q_P}{P_m\lambda_P}} \sum_{k=0}^{m_p - 1} \frac{1}{k!}\left(\frac{Q_P}{P_m\lambda_P}\right)^k\right) \\ & + \frac{u^{m_S n_R - 1}(Q_P/P_m)^{m_S n_R + m_p}(m_S n_R + m_p - 1)!}{(Q_P\lambda_S/\sigma^2)^{m_S n_R}\lambda_P^{m_P}(m_S n_R - 1)!(m_P - 1)!} \\ & \times \sum_{k=0}^{m_S n_R + m_p - 1} \frac{1}{(m_S n_R + m_p - 1 - k)!} \frac{e^{-\left(\frac{\sigma^2\lambda_P}{Q_P\lambda_S}u + 1\right)\frac{Q_P}{P_m\lambda_P}}}{\left(\left(\frac{\sigma^2\lambda_P}{Q_P\lambda_S}u + 1\right)\frac{Q_P}{P_m\lambda_P}\right)^{k+1}} . \end{aligned} \tag{15}$$

By substituting PDF in CDF definition, using change of variables, [30, eq. (2.323)] and binomial distribution, the corresponding CDF expression is obtained

$$
\begin{aligned}
F_{\gamma_{RF}}(\gamma) = {} & \left(1 - e^{-\frac{Q_P}{P_m \lambda_P}} \sum_{k_1=0}^{m_p-1} \frac{1}{k_1!}\left(\frac{Q_P}{P_m \lambda_P}\right)^{k_1}\right)\left(1 - e^{-\frac{\gamma}{P_m \lambda_S / \sigma^2}} \sum_{k_2=0}^{m_S n_R-1} \frac{1}{k_2!}\left(\frac{\gamma}{P_m \lambda_S / \sigma^2}\right)^{k_2}\right) \\
& + \sum_{k=0}^{m_S n_R + m_p - 1} \frac{(m_S n_R + m_p - 1)\;!\left(\dfrac{Q_P}{P_m \lambda_P}\right)^{m_S n_R + m_p - k - 1}}{(m_S n_R + m_p - 1 - k)!(m_S n_R - 1)!(m_P - 1)!} \sum_{l=0}^{m_S n_R - 1} \binom{m_S n_R}{l} (-1)^{m_S n_R - 1 - l} \\
& \times \left( E_{k+1-l}\left(\frac{Q_P}{P_m \lambda_P}\right) - \left(1 + \frac{\sigma^2 \lambda_P}{Q_P \lambda_S}\gamma\right)^{l-k} E_{k+1-l}\left(\left(1 + \frac{\sigma^2 \lambda_P}{Q_P \lambda_S}\gamma\right)\frac{Q_P}{P_m \lambda_P}\right)\right),
\end{aligned}
\tag{16}
$$

where $E_n(c)$ is exponential integral function defined in [29, eq. (5.1.4)].

## 3. OUTAGE ANALYSIS

In considered system, the receiver employs the MRC scheme. The instantaneous SNR of combiner output signal represents the sum of the SNRs of each sub-system, which is expressed as

$$\gamma_{eq} = \gamma_{FSO} + \gamma_{RF} , \tag{17}$$

where $\gamma_{FSO}$ is the instantaneous SNR over FSO link previously defined in eq. (2), and $\gamma_{RF}$ represents the instantaneous SNR over RF sub-system given by eq. (14).

The PDF of the MRC output is defined as [30]

$$f_{\gamma_{eq}}(z) = \int_0^z f_{RF}(z-y) f_{FSO}(y) dy , \tag{18}$$

where $f_{RF}(u)$ and $f_{FSO}(u)$ is given by eq. (5) and eq. (15), respectively.

The CDF of the MRC output is found as

$$F_{\gamma_{eq}}(\gamma) = \int_0^\gamma \int_0^z f_{RF}(z-y) f_{FSO}(y) dy dz . \tag{19}$$

The integrals in eqs. (18) and (19) have no closed form, so the final outage probability expression is evaluated numerically.

## 4. NUMERICAL RESULTS

In this Section we provide the numerical results for outage probability of hybrid cognitive RF/FSO system and highlight important effects obtained by combined use of RF and FSO systems. Theoretical values for outage performance of RF sub-system and FSO sub-system are obtained based on (7) and (16), respectively. Numerical results are confirmed using independent simulation method.

In Fig. 2 outage performance are compared for cognitive RF sub-system, FSO sub-system and hybrid RF/FSO system. Outage probability dependence on outage threshold is presented, for different values of Rytov standard deviation, which determines atmospheric turbulence strength. In weak turbulence conditions over FSO link ($\sigma_R$=0.8) and average electrical SNR $\mu_{FSO}$=25 dB, FSO sub-system shows better performances compared to cognitive RF system with $n_r$=2, $P_m$=5 dB, $Q_p$=0 dB in propagation environment with fading parameters $m_s$=$m_p$=2, $\lambda_S$=$\lambda_P$=1, $\sigma^2$=1. Also, FSO system has lower outage probability than the considered RF system for the threshold range from -3 to 20 dB in the strong turbulence condition ($\sigma_R$=5). In accordance with expectations, the hybrid cognitive RF/FSO system with MRC at the destination gives the best performances. For example, for $\gamma_{th}$=-5 dB and weak turbulence conditions, the outage performance will be improved from $2\times10^{-4}$ to $3.45\times10^{-7}$ when the transmission is performed using hybrid RF/FSO system instead of FSO system.

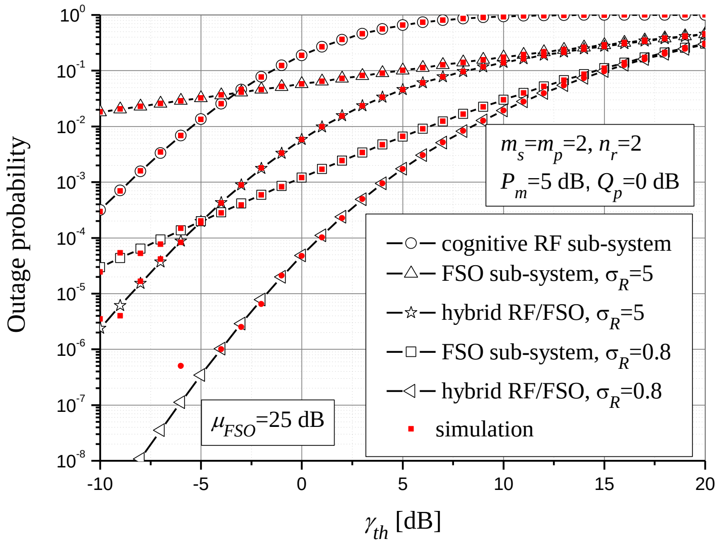


**Fig. 2** Outage probability vs. outage threshold for cognitive RF sub-system, FSO sub-system and hybrid RF/FSO system

Outage probability in the function of the average electrical SNR per FSO link for hybrid RF/FSO system is presented in Fig. 3, assuming different number of RF antennas and various RF fading conditions. Theoretical results are in accordance with the simulation ones. The system performance is significantly improved using hybrid RF/FSO system with MRC instead of FSO system only. As it is expected, system shows better performances for a larger number of antennas. It can be notices that the system performance is improved for larger values of fading parameter, as fading severity is reduced in this case and average SNR in fading channels is increased. The performance gain obtained by using $n_r$=3 antennas instead of $n_r$=2, is greater in the propagation environment with higher values of fading parameter.

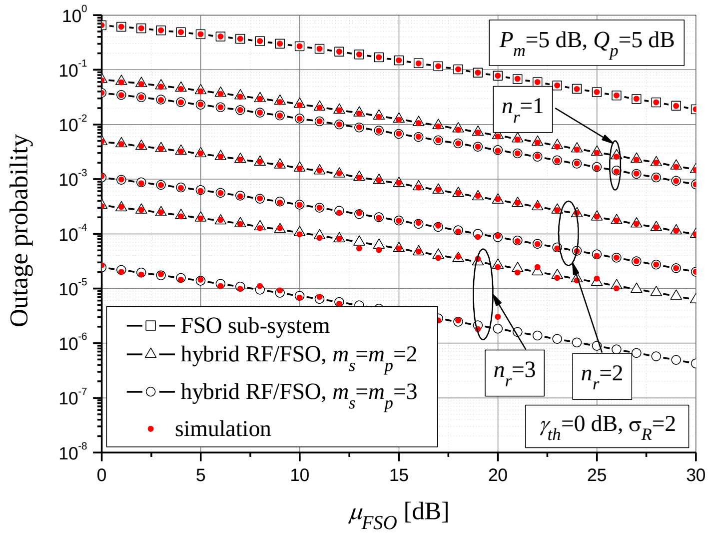


**Fig. 3** Outage probability vs. average electrical SNR per FSO link for FSO sub-system and hybrid RF/FSO system for different fading condition and number of antennas.

Fig. 4 presents the outage performance for cognitive RF/FSO system in the function of Rytov standard deviation. The numerical and simulation results are obtained for different values of the peak interference power constraint, $Q_p$, considering the parameters $m_s$=$m_p$=2, $n_r$=2, $P_m$=5 dB, $\gamma_{th}$=-0 dB and $\mu_{FSO}$=20 dB. The figure also presents the results

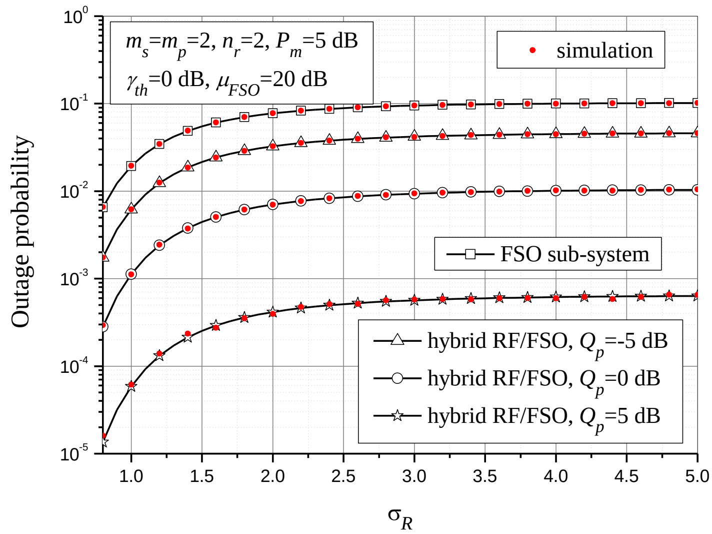


**Fig. 4** Outage probability dependence on $\sigma_R$ for FSO sub-system and hybrid RF/FSO system for different $Q_p$.

for the FSO sub-system. Outage probability values increase with $\sigma_R$, for all considered cases. For $Q_p$=-5 dB, the value of the outage probability is increased from 0.00174 to 0.04595, by changing the atmospheric turbulence condition from weak ($\sigma_R$=0.8) to strong ($\sigma_R$=5). Also, it can be noticed that the use of hybrid system significantly lowers outage probability and the outage probability performance of the RF/FSO system are better for higher values of the peak interference power constraint.

Outage performance for the cognitive RF sub-system and hybrid RF/FSO system in the function of the maximum allowable transmitter power $P_m$ are presented in Fig. 5. For lower values of $P_m$ ($P_m$<-5dB), the influence of the peak interference power constraint on the outage probability can be neglected. The increase of $P_m$ leads to the system performance improvement when $P_m$ takes the values from -5 to 5dB. Further increasing of the maximal allowable power does not lead to system performance improvement (the outage floor occurs), and the system performance is determined only by the peak interference power constraint. Also, it can be observed that the use of hybrid RF/FSO system improves outage performances compared to the use of cognitive system. For example, the hybrid RF/FSO system for $Q_p$=0dB outperforms cognitive RF system when $Q_p$=5 dB. It means that the similar system performance of cognitive RF system can be achieved by employing the hybrid RF/FSO system when the peak interference power constraint is lower (stricter condition of peak interference power constraint).

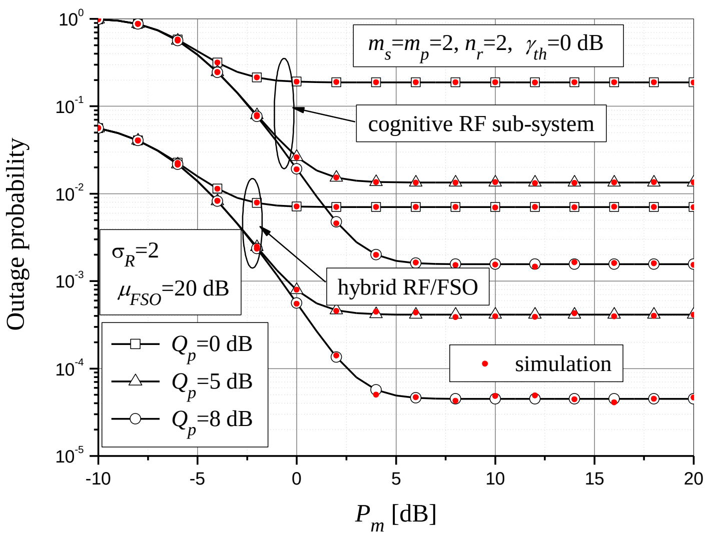


**Fig. 5** Outage probability dependence on $P_m$ for cognitive RF sub-system and hybrid RF/FSO system for different $Q_p$ values.

Fig. 6 presents the outage probability dependence on peak interference power constraint $Q_p$ for different values of maximum allowable transmitter power $P_m$. The RF sub-system with 2 antennas is considered and propagation environment with $m_s$=$m_p$=2 and $\lambda_s$=$\lambda_s$=1. In the range of lower values $Q_p$, the outage probability decreases regardless of the maximum allowable transmitter power. The outage floor appears at high values of $Q_p$, and for larger

$P_m$ the value of $Q_p$ where outage probability is saturated is larger also. The values of the outage floor decreases with the raise of maximal transmit power $P_m$ and the value of parameter $\sigma_R$.

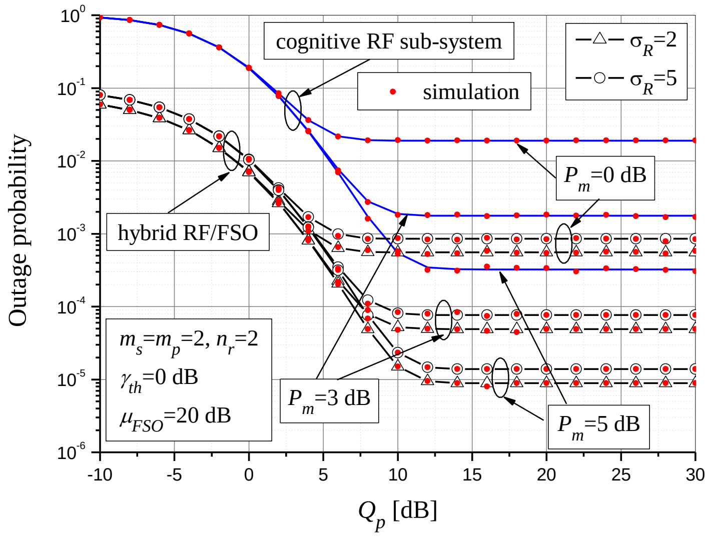


**Fig. 6** Outage probability dependence on $Q_p$ for cognitive RF sub-system and hybrid RF/FSO system for different $P_m$ values.

## 5. Conclusion

This paper presents performance analysis of the hybrid RF/FSO system, which consists of direct FSO link and cognitive RF sub-system with the MRC diversity technique applied at the receiver. Besides FSO sub-system, the considered RF signal transmission is performed by sharing the spectrum with the licensed (primary) user under the peak interference power constraint. Based on derived expressions for outage probability, numerical results are presented and confirmed by Monte Carlo simulations. The effect of the FSO and RF sub-system parameters on the outage probability is observed and the performance gain is analyzed. The presented results show that introducing the cognitive RF system as a back-up link provides better system performance that single FSO link in wide range of atmospheric conditions ensuring license-free transmission.

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