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Radio-optical line for SCADA systems with relay

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Abstract. Hybrid optical-radio communication systems provide high-speed access within the "last mile" and can act as highly reliable broadband channels of SCADA software and hardware systems. They use optical channels as the main communication lines, and radio channels as backup, since the transmission quality of atmospheric optical channels is largely determined by weather conditions. To reduce the effect of atmospheric turbulence, it is proposed to use the option of spatial diversity with line-of-sight channels and containing a repeater. When the signal-to-noise ratio decreases in the optical channel below the selected threshold, switching to the radio link is to be performed. The paper provides the results of modeling the operation of a hybrid radio-optical line in SCADA systems, in which a new switching system for optical and radio-frequency channels using a repeater is proposed. The dependences of the outage probability of the optical channel and the system as a whole are obtained.

1. Introduction

Data transmission systems using the technology of free space optics (FSO) enable to get broadband secure channels for various applications. The main reason limiting the widespread practical implementation of FSO is the strong dependence of communication quality on weather conditions. It can be significantly increased by using a hybrid communication system consisting of an FSO line and a backup radio frequency line in the millimeter wavelength range. Such systems are used as “last mile” access technologies, protected by highly reliable channels in automation and industrial communication systems. To date, the first commercial products are introduced that are involved in SCADA software and hardware systems for organizing control channels for technological processes and telemetry [1, 2].

The main reason for the decrease in communication quality in FSO lines is atmospheric turbulence affecting the optical signal in the atmospheric channel [3].

For correct analysis, the FSO system must have an accurate model that takes into account the effects of fading and scintillation caused by turbulence.

The lognormal and gamma distributions are commonly considered in studies [3]. Nevertheless, using them it is impossible to simulate illumination fluctuations for all types of turbulence and under all aperture averaging conditions [4].

In [5], [6], a new distribution was proposed, known as the Weibull-exponential distribution, which can be used to model fluctuations in the intensity of the received optical signal due to atmospheric turbulence (moderate to strong) for point optical detectors and with aperture averaging.

Further, when modelling the effect of the atmospheric channel on the FSO line, the Weibull-exponential distribution and for the RF line the Nakagami-m distribution are used [7].

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The introduction of FSO is also limited by the need to establish a line-of-sight channel, which is not always easy to obtain in urban or industrial conditions. In this case, a number of researchers propose the introduction of a backup channel with a relay [8, 9]. In this case, the receiver gets information messages arriving on independent channels. Shared data transmission at the same time significantly improves the quality of communication.

2. System model

The proposed model of a hybrid radio-optical transmission system is shown in Figure 1. Here we used a line-of-sight and a channel with a repeater operating in the "decoding and forward" (DF) mode. At the same time, no increase in the noise level occurs in the repeater channel [10].

In all channels, the main transmission line is FSO, provided that the instantaneous signal-to-noise ratio at the receiver input is above a predefined threshold. When it falls below the threshold level, switching to the RF line occurs.

Signals are transmitted using binary phase-shift keying. In the optical channels, transmitters with intensity modulation and incoherent receivers are used.

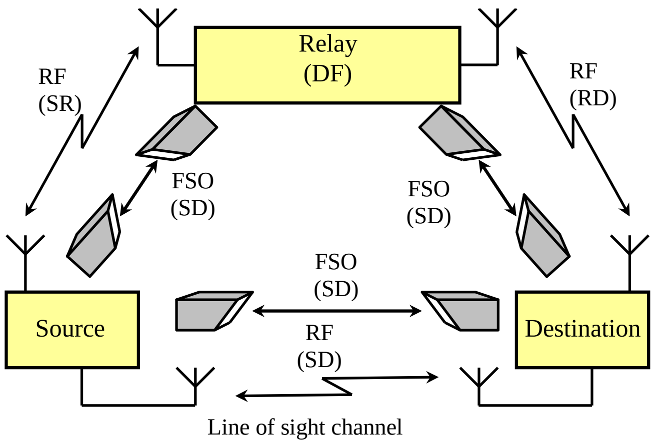

Figure 1. The structure of a hybrid transmission system.

Denote the instantaneous signal-to-noise ratio of the RF lines as $\gamma_{AB}^{RF} = \bar{\gamma}_{AB}^{RF} K_{AB}^2$ where $\bar{\gamma}_{AB}^{RF}$ - the average signal-to-noise ratio of the radio frequency line, K_{AB} – the transmission coefficient in the radio frequency channel with fading, AB ∊ {SR, SD, RD}. As mentioned above, to simulate the transmission coefficient of the RF channels, we use the Nakagami-m distribution. The cumulative distribution function (CDF) γ_{AB}^{RF} has the form [7]:

$$F_{AB}^{RF}(\gamma) = \int_0^{\gamma} p_{AB}^{RF}(\gamma) d\gamma = \frac{1}{\Gamma(m)} \gamma\left(m, \frac{\gamma m}{\bar{\gamma}_{AB}^{RF}}\right), \tag{1}$$

where $\gamma(\cdot, \cdot)$ – lower incomplete gamma function, $p_{AB}^{RF}(\gamma)$ - the probability density function (PDF) of a quantity γ_{AB}^{RF} is described by a gamma distribution [8-10]:

$$p_{AB}^{RF}(\gamma) = \left[\frac{m}{\bar{\gamma}_{AB}^{RF}}\right]^m \frac{(\gamma)^{m-1}}{\Gamma(m)} e^{-\frac{m\gamma}{\bar{\gamma}_{AB}^{RF}}}, \tag{2}$$

where $\Gamma(\cdot)$ – gamma function.

For FSO similarly set the instantaneous γ_{AB}^{FSO} and average $\bar{\gamma}_{AB}^{FSO}$ signal-to-noise ratio. When using the exponential distribution of the Weibull, the CDF value γ_{AB}^{FSO} is equal to [8-10]:

$$F_{AB}^{FSO}(\gamma)=\left\{1-\exp\left[-\left(\frac{1}{\eta}\sqrt{\frac{\gamma}{\bar{\gamma}_{AB}^{FSO}}}\right)^{\beta}\right]\right\}^{\alpha}. \tag{3}$$

Distribution coefficient α is defined as:

$$\alpha=3{,}931\left(\frac{D_R}{\rho_0}\right)^{-0{,}519} \tag{4}$$

where D_R - receiver aperture diameter, $\rho_0=(1{,}46C_n^2k^2L)^{-3/5}$ - atmospheric coherence radius, C_n^2 - turbulence structural constant, k - wave number, L - the length of the communication channel.

The parameter β is set as $\beta=(\alpha\sigma_I^2)^{-6/11}$, where σ_I^2 - scintillation index.

The coefficient η is determined according to [8-10]:

$$\eta=\frac{1}{\alpha\Gamma(1+1/\beta)g(\alpha,\beta)}, \text{ where } g(\alpha,\beta)=\sum_{i=9}^{\infty}\frac{(-1)^i(i+1)^{-\frac{1=\beta}{\beta}}\Gamma(\alpha)}{i!\Gamma(\alpha-i)}. \tag{5}$$

PDF values γ_{AB}^{FSO} can be calculated using the expression:

$$p_{AB}^{FSO}(\gamma)=\frac{\alpha\beta}{2\bar{\gamma}_{AB}^{FSO}\eta^{\beta}}\left(\sqrt{\frac{\gamma}{\bar{\gamma}_{AB}^{FSO}}}\right)^{\beta-2}\exp\left[-\left(\frac{1}{\eta}\sqrt{\frac{\gamma}{\bar{\gamma}_{AB}^{FSO}}}\right)^{\beta}\right]\left\{1-\exp\left[-\left(\frac{1}{\eta}\sqrt{\frac{\gamma}{\bar{\gamma}_{AB}^{FSO}}}\right)^{\beta}\right]\right\}^{\alpha-1}. \tag{6}$$

The optical receiver, based on the value of a predetermined threshold, must select the highest signal-to-noise ratio among the SD and RD signals. Moreover, for the entire system as a whole, the signal-to-noise ratio γ_Σ is defined as $\gamma_\Sigma=\max(\gamma_{SD},\gamma_{RD})$. When transmitting along the FSO, the values CDF γ_Σ^{FSO} and γ_Σ^{RF} may be expressed as:

$$F_\Sigma^{FSO}=F_{SD}^{FSO}(\gamma)F_R^{FSO}(\gamma),\ F_\Sigma^{RF}=F_{SD}^{RF}(\gamma)F_R^{RF}(\gamma) \tag{7}$$

Here, $F_R^{FSO}(\gamma)$ and $F_R^{RF}(\gamma)$ - CDF of the signal-to-noise ratio in the channel with the repeater, which is determined by the worst case, i.e. $\gamma_R=\min(\gamma_{SR},\gamma_{RD})$:

$$\begin{aligned}&F_R^{FSO}(\gamma)=P[\min(\gamma_{SR}^{FSO},\gamma_{RD}^{FSO})<\gamma]=1-P(\gamma_{SR}^{FSO}>\gamma)P(\gamma_{RD}^{FSO}>\gamma)=\\&=1-[1-P(\gamma_{SR}^{FSO}<\gamma)][1-P(\gamma_{RD}^{FSO}<\gamma)],\\&F_R^{RF}(\gamma)=P[\min(\gamma_{SR}^{RF},\gamma_{RD}^{RF})<\gamma]=1-P(\gamma_{SR}^{RF}>\gamma)P(\gamma_{RD}^{RF}>\gamma).\end{aligned} \tag{8}$$

Indicated values $\gamma_{SR}^{FSO},\gamma_{SR}^{RF}$ and $\gamma_{RD}^{FSO},\gamma_{RD}^{RF}$ are signal-to-noise ratios for SR and RD channels in the case of transmission over FSO and RF lines, respectively. Then the CDF of the signal-to-noise ratio in the channel with the repeater is determined as follows:

$$F_R^{FSO}(\gamma)=1-\exp\left[-\left(\frac{1}{\eta}\sqrt{\frac{\gamma}{\bar{\gamma}_{SR}^{FSO}}}\right)^{\beta}\right]^{\alpha}\cdot\exp\left[-\left(\frac{1}{\eta}\sqrt{\frac{\gamma}{\bar{\gamma}_{RD}^{FSO}}}\right)^{\beta}\right]^{\alpha}, \tag{9}$$

$$F_R^{RF}(\gamma)=1-\frac{\Gamma\left(m,\frac{\gamma m}{\bar{\gamma}_{SR}^{RF}}\right)}{\Gamma(m)}\cdot\frac{\Gamma\left(m,\frac{\gamma m}{\bar{\gamma}_{RD}^{RF}}\right)}{\Gamma(m)}. \tag{10}$$

Corresponding PDF values are obtained due to differentiation of CDF γ_Σ^{FSO} and γ_Σ^{RF} by γ. Using expressions (1-3), (6), (9-10) obtain:

$$p_R^{RF}(\gamma)=\left(\frac{m}{\bar{\gamma}_{SR}^{RF}}\right)^m\frac{\gamma^{m-1}}{\Gamma(m)}e^{-\frac{m\gamma}{\bar{\gamma}_{SD}^{RF}}}+\left(\frac{m}{\bar{\gamma}_{RD}^{RF}}\right)^m\frac{\gamma^{m-1}}{\Gamma(m)}e^{-\frac{m\gamma}{\bar{\gamma}_{RD}^{RF}}}--\left(\frac{m}{\bar{\gamma}_{SR}^{RF}}\right)^m\frac{\gamma^{m-1}}{\Gamma(m)}e^{-\frac{m\gamma}{\bar{\gamma}_{SR}^{RF}}}\frac{1}{\Gamma(m)}\gamma\left(m,\frac{\gamma m}{\bar{\gamma}_{RD}^{RF}}\right)- \tag{11}$$
$$-\left(\frac{m}{\bar{\gamma}_{RD}^{RF}}\right)^m\frac{\gamma^{m-1}}{\Gamma(m)}e^{-\frac{m\gamma}{\bar{\gamma}_{RD}^{RF}}}\frac{1}{\Gamma(m)}\gamma\left(m,\frac{\gamma m}{\bar{\gamma}_{SR}^{RF}}\right),$$

$$p_R^{FSO}(\gamma)=\frac{\alpha\beta}{2\gamma}\left[\left(\frac{1}{\eta}\sqrt{\frac{\gamma}{\bar{\gamma}_{RD}^{FSO}}}\right)^\beta+\left(\frac{1}{\eta}\sqrt{\frac{\gamma}{\bar{\gamma}_{SR}^{FSO}}}\right)^\beta\right]\exp\left[-\left(\frac{1}{\eta}\sqrt{\frac{\gamma}{\bar{\gamma}_{RD}^{FSO}}}\right)^\beta\right]^\alpha\exp\left[-\left(\frac{1}{\eta}\sqrt{\frac{\gamma}{\bar{\gamma}_{SR}^{FSO}}}\right)^\beta\right]^\alpha. \tag{12}$$

The PDF of the hybrid FSO/RF system is further obtained when transmitting through the FSO and RF channels, respectively:

$$p_\Sigma^{FSO}(\gamma)=F_{SD}^{FSO}(\gamma)p_R^{FSO}(\gamma)+p_{SD}^{FSO}(\gamma)F_R^{FSO}(\gamma),\ p_\Sigma^{RF}(\gamma)=F_{SD}^{RF}(\gamma)p_R^{RF}(\gamma)+p_{SD}^{RF}(\gamma)F_R^{RF}(\gamma) \tag{13}$$

An outage condition in the communication system occurs if the instantaneous signal-to-noise ratios of the FSO and RF lines fall below the set thresholds γ_T^{FSO} and γ_T^{RF} respectively.

The expression for the outage probability of P_o is defined as:

$$P_o=F_\Sigma^{FSO}(\gamma_T^{FSO})F_\Sigma^{RF}(\gamma_T^{RF}), \tag{14}$$

The average bit error rate is determined for quadrature phase shift keying (MPSK) at equal transmission rates in the FSO and RF lines. The conditional probability of a bit error when transmitting MPSK signals with an instantaneous signal-to-noise ratio γ on any line is given by the expression [7]:

$$P_{MPSK}(\gamma)=\frac{1}{\log_2 M}erfc\left(\sqrt{\gamma}\sin(\pi/M)\sqrt{\log_2 M}\right)\cdot \tag{15}$$

The average value of the bit error rate of the hybrid FSO / RF P_{BER} is determined based on the average bit errors of the FSO and RF lines as follows:

$$P_{BER}=\frac{P_\Sigma^{FSO}(\gamma_T^{FSO})+F_\Sigma^{FSO}(\gamma_T^{FSO})P_\Sigma^{RF}(\gamma_T^{RF})}{1-P_o}, \tag{16}$$

where $P_\Sigma^{FSO}(\gamma_T^{FSO})$ and $P_\Sigma^{RF}(\gamma_T^{RF})$ are FSO and RF channel bit errors, respectively.

The average value of the bit error rate in the FSO, provided that $\gamma_\Sigma^{FSO}>\gamma_T^{FSO}$ can be defined as:

$$P_\Sigma^{FSO}(\gamma)=\int_{\gamma_T^{FSO}}^{\infty}P_{MPSK}(\gamma)p_\Sigma^{FSO}(\gamma)d\gamma\cdot \tag{17}$$

Similarly, the average bit error rate for the RF line is set when $\gamma_\Sigma^{RF}>\gamma_T^{RF}$:

$$P_\Sigma^{RF}(\gamma)=\int_{\gamma_T^{RF}}^{\infty}P_{MPSK}(\gamma)f_\Sigma^{RF}(\gamma)d\gamma\cdot \tag{18}$$

Substituting (17) and (18) into (16), the average bit error rate of the hybrid FSO/ RF system with a relay is obtained.

3. Numerical simulations

In the simulation, we used the Nakagami distribution parameter $m = 3$, the modulation type BPSK, i.e. $M = 2$, and the average signal-to-noise ratio in the channels was considered the same. Figure 2 shows the dependences of the outage probability P_o on the average signal-to-noise ratio of the FSO line $\bar{\gamma}_\Sigma^{FSO}$ for the case of weak (σ_I^2=0.2) and strong (σ_I^2=5) turbulence.

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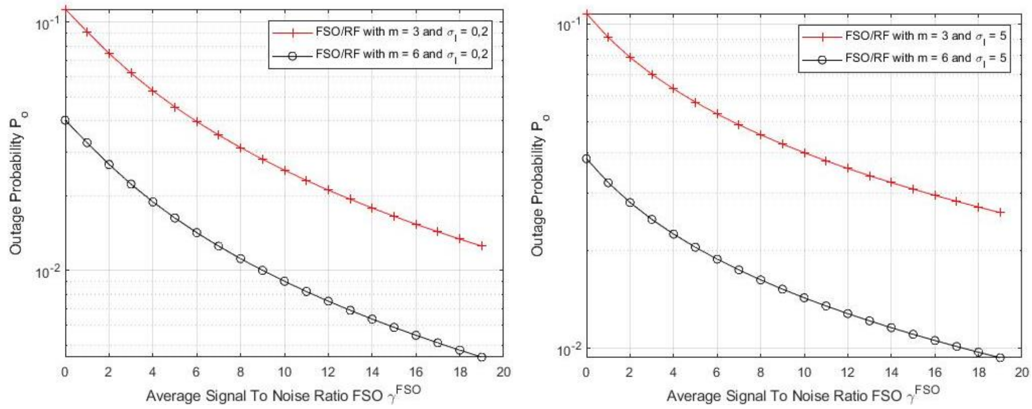

Figure 2. The outage probability in the signal-to-noise ratio function of the FSO.

It can be seen that in cases of m = 3 and m = 6 the quality of communication is almost the same. However, with an increase σ_I^2 quality of communication is expected to decline.

Figure 3 shows the dependence of P_o n the average signal-to-noise ratio in the FSO for fixed γ_T^{FSO} and γ_T^{RF}. Even with low quality of the RF channel ($\bar{\gamma}^{RF}$ = 5 dB) the proposed system works better than the single-channel FSO system.

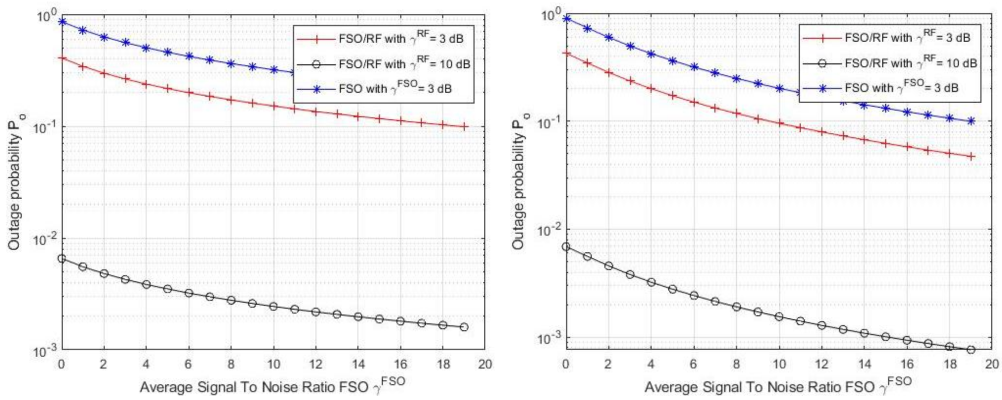

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Figure 3. The outage probability in the signal-to-noise ratio function of the FSO.

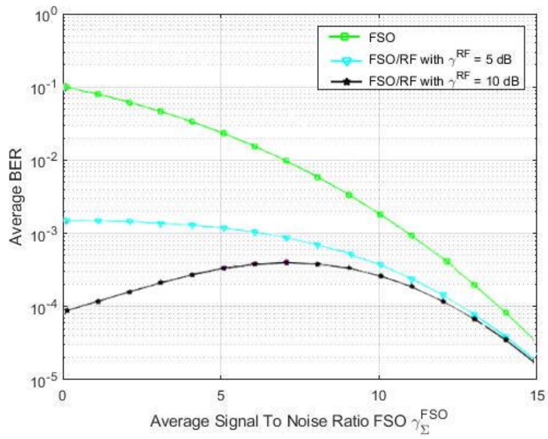

Figure 4. FSO/RF system bit error rate.

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Figure 4 shows the dependence of the bit error rate on the average signal-to-noise ratio on the FSO for various $\bar{\gamma}^{RF}$.

The FSO/RF hybrid system has a bit error rate lower than that of a single FSO line, since at low levels $\bar{\gamma}^{FSO}$ the communication is supported by the RF line. With growth of $\bar{\gamma}^{FSO}$ the system uses the FSO channel, which leads to an increase of the bit error rate. However, further growth of $\bar{\gamma}^{FSO}$ will again reduce the likelihood of a bit error.

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