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Research on Communication Technology of OPGW Line in Distribution Network under Interference Environment

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Abstract

In optical fiber composite overhead ground wire (OPGW) networks, the current monitoring is mainly through installing electronic sensors on the cable and manually monitoring the video on the cable, where the interference plays an important role in the communication and monitoring based systems. In essence, the interference arises from aggressive frequency reuse, especially in the frequency-limited Internet of Things (IoT) networks. The existence of interference causes a negative effect on the system performance of communication systems and IoT networks including the OPGW networks. Hence, this article investigates the communication technology of OPGW line in distribution network under interference environment, where there is one primary link, one secondary link, and one legitimate monitor listening to the secondary link. The secondary user needs to transmit its message to the secondary receiver under the interference power constrained by the primary node. We firstly define the outage probability of legitimate monitoring based on the data rate, and then analyze the system performance by theoretically deriving a closed-form expression of the outage probability for the OPGW communication under interference environment. Simulation results are finally demonstrated to verify the correctness of the closed-form expression for the OPGW communication under interference environment, and show that the interference has a negative impact on the OPGW communication performance.

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Keywords: Data transmission, outage probability, analytical expression, interference, OPGW communication.

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1. Introduction

Promoted by advanced information technology [1, 2], especially the scalable information systems [3, 4], high voltage overhead power lines have become an important part of the transmission network [5, 6]. Due to the influence of layout factors, the terrain and ground conditions in the corridor area are complicated and changeable, such as high altitude, windy and frozen areas. These micro-environments cause various kinds of environmental disasters of overhead power lines in a variety of harsh environments, such as icing, mountain fire, lightning strikes, instant gales, etc [7, 8]. At the same time, the overhead power lines need to operate for a long time. In addition to the common fault defects such as line aging and disconnection, they will also cause serious accidents such as conductor galloping, tower tilt and even collapse due to coupling with environmental problems, which seriously threaten the safe and stable operation of the power transmission system. The terrain of the area where the overhead line passes is complicated, and the span is hundreds of kilometers. The cost of traditional manual or helicopter inspection and monitoring is getting higher and higher.

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A lot of problems exist such as long monitoring period, low work efficiency, and the monitoring results are vulnerable to human factors.

Optical fiber composite overhead ground wires (OPGW) is the physical carrier of power communication network and an important infrastructure for safe operation of power grid. During long-term operation, OPGW cable will inevitably encounter extreme weather such as ice coating, wind and sand, as well as tension caused by overhead suspension, which will greatly affect the transmission performance of the cable. With the increase of service life, the number of failures of OPGW optical cable is also increasing. However, the fault location and disposal of OPGW optical cable should be carried out during the line outage, and the average fault disposal time is the longest of all kinds of faults. Therefore, accurate and fast fault location of OPGW optical cable has become the pain point and difficult problem in the power grid safety production.

Currently, for fault location of OPGW optical cable, the method of testing breakpoints with optical time domain reflectometer (OTDR) is used in practical operation and maintenance works. Due to factors such as optical cable sag and excess length of optical fiber, the measured optical fiber length at the optical cable fault point has an average error of about kilometers compared with the total corresponding tower span. This leads to the use of manual line patrol method within the range of several thousand meters after the OTDR test breakpoint, or even open the nearby optical cable junction box for accurate positioning of the breakpoint during the line outage maintenance. Generally, it takes about 1.5 day to locate an OPGW cable fault on average, and the fault location efficiency is low.

The global distribution of clean energy resources is uneven. To realize the large-scale development and utilization of clean energy, it is necessary to build an energy network with clean leadership, electricity as the center, and global configuration capabilities. The energy internet is a strong smart grid with ultra-high voltage power grid as the backbone grid and global interconnection. It is bound to build a large capacity, long-distance and highly reliable power information communication system to provide necessary ways for global energy internet scheduling, operation, management, operation, etc.

The interference plays an important role in the communication and monitoring oriented systems, including the considered OPGW networks [9–11]. In essence, the interference arises from aggressive frequency reuse, especially in the frequency-limited Internet of Things (IoT) networks [12–14]. The existence of interference causes a negative effect on the system performance of communication systems and IoT networks including the OPGW networks [15–17]. For example, the data transmission rate of the system will be deteriorated when the interference exists, which reduces the received signal-to-noise ratio (SNR) at the receiver or monitoring node [18, 19]. The detection performance such as symbol error rate (SER) can be also deteriorated by the arising interference, as the interference will affect the work mechanism of the detector or monitor. In addition, the interference will affect the transmission latency [20–22] and energy consumption [23–25], which increases the communication and computing cost for the IoT networks including the OPGW networks. Hence, it becomes an important task to investigate the effect of interference on the IoT based OPGW networks, especially the monitoring performance.

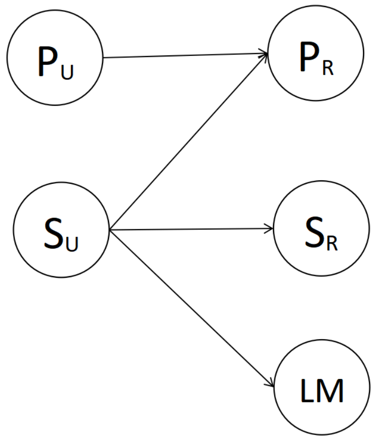

Figure 1. System model of the OPGW communication under interference environment.

In this article, we investigate the communication technology of OPGW line in distribution network under interference environment, where there is one primary link, one secondary link, and one legitimate monitor listening to the secondary link. The secondary user needs to transmit its message to the secondary receiver under the interference power constrained by the primary node. To evaluate the system performance, we firstly define the outage probability of legitimate monitoring according to the transmission data rate and monitoring data rate, and then study the system outage probability by deriving an analytical expression for the OPGW communication under interference environment. Simulation results are finally presented to verify the correctness of the closed-form expression for the OPGW communication under interference environment, and show that the OPGW communication performance can be severely deteriorated by the interference.

2. System model of OPGW communication under interference environment

As shown in Fig.1, we consider an OPGW communication under interference environment, where there is a cognitive radio network composed of one primary node, one secondary node, and one legitimate monitoring node. The primary user (P_U) transmits message to the primary receiver (P_R), and the secondary user (S_U) transmits message to the secondary receiver (S_R) under the monitoring of the legitimate monitor (LM). Due to the interference power constraint, the transmit power of the secondary user can be given by [26–28]

$$P = \frac{I_p}{\left|h_p\right|^2}, \tag{1}$$

where I_p is the tolerated peak interference power on the primary receiver, and h_p is the channel parameter of the link between S_U and P_R subject to Rayleigh flat fading.

Thus, the signal-to-noise ratios (SNRs) of the secondary link and the monitoring link are given by [29, 30]

$$\mathrm{SNR}_{S_U} = \frac{P\left|h\right|^2}{\sigma^2}, \tag{2}$$

$$\mathrm{SNR}_{LM} = \frac{P\left|g\right|^2}{\sigma^2}, \tag{3}$$

where h and g denote the channel parameters of the secondary link and monitoring link, respectively. Notation σ^2 is the AWGN variance at the S_U and LM.

The LM needs to monitor the secondary link, and the unified corresponding monitoring data rate can be given by

$$R_{LM} = \log_2\left(1 + SNR_{LM}\right) - \log_2\left(1 + SNR_{S_U}\right) \tag{4}$$

$$= \log_2\left(\frac{1 + SNR_{LM}}{1 + SNR_{S_U}}\right). \tag{5}$$

3. Performance analysis of the OPGW communication under interference environment

In this section, we first give the definition on the outage probability of the legitimate monitoring, and then we derive the closed-form expression of the system outage probability.

In order to ensure the legitimate monitoring, we first define the outage probability as

$$P_{out} = \Pr\left(R_{LM} < \gamma_{th}\right), \tag{6}$$

$$= \Pr\left(\log_2 \frac{1 + SNR_{LM}}{1 + SNR_{S_U}} < \gamma_{th}\right), \tag{7}$$

$$= \Pr\left(\left|h_p\right|^2 < \frac{I_p(2^{\gamma_{th}}\left|h\right|^2 - \left|g\right|^2)}{\sigma^2(1 - 2^{\gamma_{th}})}\right), \tag{8}$$

where γ_{th} is the data rate threshold for monitoring the network and it is used to guarantee the quality of monitoring.

Then, we begin to derive the analytical form of P_{out}. The average gain of the link between S_U and P_R is β_I, and according to the cumulative distribution function (CDF) of $\left|h_p\right|^2$, we can have

$$P_{out} = F_{\left|h_p\right|^2}(x)\Big|_0^{\frac{I_p(2^{\gamma_{th}}|h|^2 - |g|^2)}{\sigma^2(1-2^{\gamma_{th}})}} \tag{9}$$

$$= 1 - e^{-\frac{I_p(2^{\gamma_{th}}\left|h\right|^2 - \left|g\right|^2)}{\beta_I\sigma^2(1 - 2^{\gamma_{th}}))}}. \tag{10}$$

The average gain of the secondary link and the monitoring link are β_h and β_g, respectively. Hence, we can then have

$$P_{out} = \int_0^{+\infty} \frac{1}{\beta_h} e^{\frac{-|h|^2}{\beta_h}} \int_0^{2^{\gamma_{th}}|h|^2} \frac{u}{\beta_g} e^{\frac{-|g|^2}{\beta_g}}\, d\left|g\right|^2\, d\left|h\right|^2, \tag{11}$$

with

$$u = \left(1 - e^{-\frac{I_p(2^{\gamma_{th}}\left|h\right|^2 - \left|g\right|^2)}{\beta_I\sigma^2(1 - 2^{\gamma_{th}})}}\right). \tag{12}$$

After some manipulations, we can further have,

$$P_{out} = \frac{1}{\beta_h}\int_0^{+\infty} e^{\frac{-|h|^2}{\beta_h}}\left[1 - e^{\frac{-2^{\gamma_{th}}|h|^2}{\beta_g}} + v\left(e^{-\frac{2^{\gamma_{th}}|h|^2}{\beta_g}} - e^{-a}\right)\right] d\left|h\right|^2,$$

with

$$v = \frac{\beta_I\sigma^2(1 - 2^{\gamma_{th}})}{\beta_I\sigma^2(1 - 2^{\gamma_{th}}) - I_p\beta_g}, \tag{13}$$

$$a = \frac{I_p 2^{\gamma_{th}}\left|h\right|^2}{\beta_I\sigma^2(1 - 2^{\gamma_{th}})}. \tag{14}$$

Finally, we can obtain the closed-form expression for the outage probability, which is given by

$$P_{out} = 1 - \frac{\beta_g}{\beta_g + 2^{\gamma_{th}}\beta_h} + v\beta_h\left(\frac{\beta_g}{\beta_g + \beta_h 2^{\gamma_{th}}} - b\right), \tag{15}$$

with

$$b = \frac{\beta_I\sigma^2(1 - 2^{\gamma_{th}})}{\beta_I\sigma^2(1 - 2^{\gamma_{th}}) + I_p 2^{\gamma_{th}}\beta_h}. \tag{16}$$

We now analyze some asymptotic behavior of the system outage probability, when the tolerated interfering power is large. Specifically, when I_P becomes large, we can approximate v from (13) as,

$$v \approx 0. \tag{17}$$

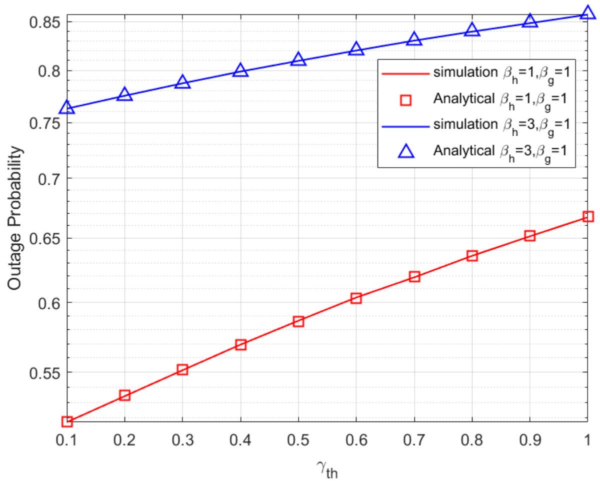

Figure 2. Monitoring outage probability of the OPGW communication under interference environment versus the threshold γ_{th}.

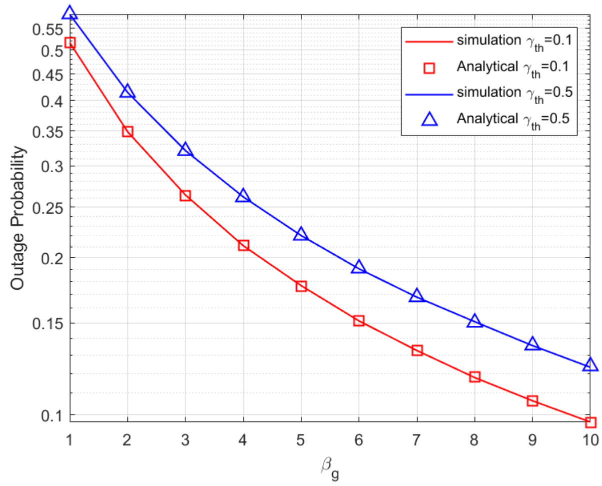

Figure 3. Monitoring outage probability of the OPGW communication under interference environment versus the average channel gain β_g.

By applying this approximation into (15), we can further approximate P_{out} as,

$$P_{out} \approx 1 - \frac{\beta_g}{\beta_g + 2^{\gamma_{th}}\beta_h}, \quad (18)$$

$$= \frac{2^{\gamma_{th}}\beta_h}{\beta_g + 2^{\gamma_{th}}\beta_h}. \quad (19)$$

From this asymptotic expression of P_{out}, we can find that the system outage probability almost linearly increases with the value of β_h, while it almost linearly decreases with the value of β_g.

In next section, we will conduct some simulations to verify the correctness of the derived closed-form expression of P_{out}.

4. Simulation results and discussions on OPGW communication under interference environment

In this section, we show some simulations of the OPGW communication under interference environment, to verify the proposed studies. If not specified, the environment setup of the simulations is set as follows: the variance of AWGN is set to $\sigma^2 = 0.01$, the interference power constraint is set to I_p = 5dB, the outage threshold is set to $\gamma_{th} = 0.1$, and $\beta_I = 1$, $\beta_h = 1$, $\beta_g = 1$. Fig. 2 shows the simulation and analytical result of the monitoring outage probability of the OPGW communication under interference environment versus the threshold γ_{th}, where the threshold γ_{th} varies from 0.1 bps to 1 bps, and the β_h is set to 1 or 3, the value of β_g is set to 1. From Fig. 2, we can see that the monitoring link's outage probability increases as the outage threshold increases, showing that a smaller γ_{th} leads to an increase in the outage performance. Moreover, the analytical results overlap with the image of the simulation results, which verifies the closed-form solution. In further, the outage probability with $\beta_h = 3$ is higher than that with $\beta_h = 1$. This is because that better secondary link channel will deteriorates the performance of the legitimate monitoring. Fig. 3 depicts the simulation and analytical outage probabilities of the OPGW communication under interference environment, versus the average channel gain of β_g, where β_g varies from 1 to 10, and the γ_{th} is set to 0.1 bps and 0.5 bps. From Fig. 3, we can observe that with the increase of β_g, the outage probability shows a significant downward trend, which is because when β_g increases, the SNR at the

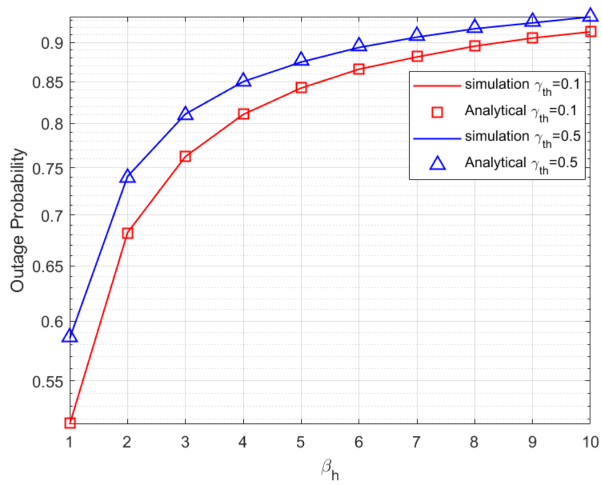

Figure 4. Monitoring outage probability of the OPGW communication under interference environment versus the average channel gain β_h.

Table 1 Data for Fig.2

γ_{th}	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
Sim:$\beta_h = 1$	0.51709	0.53402	0.55152	0.56933	0.58647	0.60362	0.61889	0.63567	0.65124	0.66689
Ana:$\beta_h = 1$	0.51739	0.53474	0.55201	0.56915	0.58613	0.60291	0.61945	0.63572	0.65169	0.66733
Sim:$\beta_h = 3$	0.76299	0.77537	0.78742	0.79901	0.80966	0.82012	0.83028	0.83957	0.84844	0.85754
Ana:$\beta_h = 3$	0.76287	0.77528	0.78723	0.79871	0.80973	0.82029	0.83038	0.84003	0.84923	0.858

Table 2 Data for Fig.3

β_g	1	2	3	4	5	6	7	8	9	10
Sim:$\gamma_{th} =$ 0.1	0.51702	0.34885	0.26386	0.2109	0.17683	0.15133	0.13281	0.11786	0.10639	0.096875
Ana:$\gamma_{th} =$ 0.1	0.51739	0.34896	0.26326	0.21135	0.17654	0.15158	0.1328	0.11816	0.10643	0.096815
Sim:$\gamma_{th} =$ 0.5	0.58582	0.41496	0.32098	0.26162	0.2206	0.19048	0.16807	0.15082	0.13571	0.12334
Ana:$\gamma_{th} =$ 0.5	0.58613	0.41446	0.32057	0.26136	0.22061	0.19086	0.16817	0.15031	0.13588	0.12397

Table 3 Data for Fig.4

β_h	1	2	3	4	5	6	7	8	9	10
Sim:$\gamma_{th} =$ 0.1	0.51634	0.68245	0.76238	0.81055	0.84224	0.86568	0.88122	0.89523	0.90586	0.91408
Ana:$\gamma_{th} =$ 0.1	0.51739	0.68198	0.76287	0.81097	0.84285	0.86554	0.8825	0.89567	0.90619	0.91478
Sim:$\gamma_{th} =$ 0.5	0.5851	0.7406	0.81098	0.8502	0.87472	0.8935	0.90702	0.91818	0.92606	0.9342
Ana:$\gamma_{th} =$ 0.5	0.58613	0.73923	0.80973	0.85028	0.87661	0.8951	0.90878	0.91933	0.9277	0.93451

Table 3 Data for Fig.5

I_p	1	2	3	4	5	6	7	8	9	10
Sim:$\gamma_{th} =$ 0.1	0.51751	0.5169	0.5172	0.51714	0.51691	0.51767	0.51775	0.51705	0.51803	0.51692
Ana:$\gamma_{th} =$ 0.1	0.51767	0.5175	0.51744	0.51741	0.51739	0.51738	0.51737	0.51737	0.51736	0.51736
Sim:$\gamma_{th} =$ 0.5	0.58639	0.58644	0.58642	0.58567	0.5864	0.58615	0.58684	0.58602	0.58561	0.5869
Ana:$\gamma_{th} =$ 0.5	0.58751	0.58665	0.58636	0.58622	0.58613	0.58607	0.58603	0.586	0.58598	0.58596

legitimate monitor's end will be better than that at the receiver's end. And it can be observed that the increase of the outage threshold γ_{th} increases the outage probability, which corresponds to the conclusion of Fig. 3. Additionally, the analytical curve perfectly replicates the simulated outcome, demonstrating the validity of the derived analytical expression.

Fig. 4 shows the simulation and analytical outage probabilities of the OPGW communication under interference environment, versus the average channel gain of β_h. In this simulation, the γ_{th} is set to 0.1 bps and 0.5 bps. The Fig. 4 shows that as β_h grows, the outage probability shows an increasing trend. This is because when h increases, the channel condition at the receiver become better than it at the legitimate monitor. In addition, the analytical conclusions fit well to the simulation results, which support the effectiveness of the derived closed-form outage probability. Fig. 5 shows the simulation and analytical outage probabilities of the OPGW communication under interference environment, versus the interference power constrain I_p, where the interference power constrain I_p varies

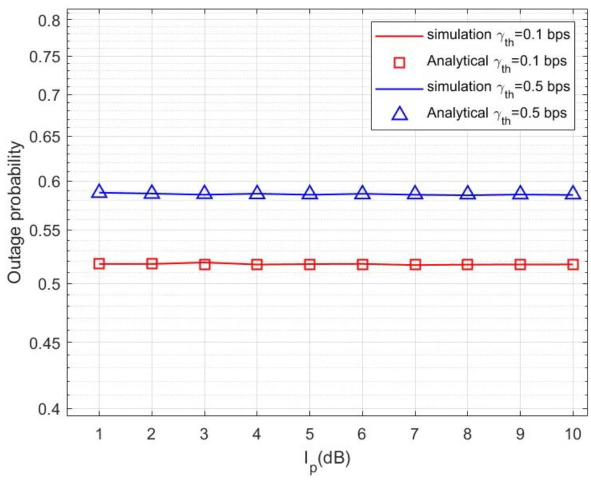

Figure 5. Monitoring outage probability of the OPGW communication under interference environment versus the interference power constrain I_p.

from 1 dB to 10 dB. From Fig. 5, we can see that the outage probability of the monitoring link does not increase due to the increase in I_p, indicate that I_p does not have an impact on the outage probability. Moreover, the analytical results match the simulation results, which validates the closed-form solution. In further, the outage probability with $\gamma_{th} = 0.5$ bps is higher than that with $\gamma_{th} = 0.1$ bps. This is because that bigger threshold γ_{th} will deteriorates the performance of the legitimate monitoring.

5. Conclusions

For the monitoring of optical fiber composite overhead ground wire (OPGW) cable, the current common methods mainly include monitoring by installing electronic sensors on the cable and manually monitoring the video on the cable, where the interference plays an important role in the communication and monitoring based systems, including the considered OPGW networks. In essence, the interference arises from aggressive frequency reuse, especially in the frequency-limited Internet of Things (IoT) networks. The existence of interference causes a negative effect on the system performance of communication systems and IoT networks including the OPGW networks. Hence, this article investigates the communication technology of OPGW line in distribution network under interference environment, where there is one primary link, one secondary link, and one legitimate monitor listening to the secondary link. The secondary user needs to transmit its message to the secondary receiver under the interference power constraint. Specifically, we define the outage probability of legitimate monitoring. Then, by analyzing the considered network, we theoretically derive a closed-form expression for the outage probability for the OPGW communication under interference environment. Simulation results finally verify the correctness of the closed-form expression for the OPGW communication under interference environment, and shows that the interference has a significant impact on the OPGW communication performance.

5.1. Data Availability Statement

The data of this work can be obtained through the email to the authors: Bo Li (bolicsg@126.com), Meiqin Huang (meiqinhuang2022@126.com), Huanyu Zhang (HuanyuHuang@hotmail.com), Mi Lin (MiLinCSG@hotmail.com), Shuyi He (ShuyiHe2022@hotmail.com), and Liming Chen (lmchen_CSPG@hotmail.com).

5.2. Copyright

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