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Blind Detection for Serial Relays in Free Space Optical Communication Systems

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Featured Application: In this work, an uncomplicated blind detection method is used for Free-space optical (FSO) communications. This detection method allows an efficient use of the data rate. Moreover, an analytical model of the proposed system is derived that allows a better understanding of the proposed system.

Abstract: Free-space optical (FSO) communication systems have attracted considerable research interest owing to its high transmission rates and its efficient solution for the last mile problem. Atmospheric turbulence degrades the performance of FSO systems. To estimate the received signal, Channel State Information (CSI) or blind detection is used. The blind detection estimates the received signal without the need for pilot signals which reduce the throughput and increase the complexity of the signal. In this paper, we have proposed a relay technique which utilizes the blind detection method for FSO communications. This proposed technique would improve the performance of the FSO system compared to the direct link method. It is observed that the proposed method achieves a signal-to-noise ratio (SNR) close to the SNR reported by CSI method maintaining the same average bit error rate, provided that only a small observation window is employed. Moreover, Monte Carlo simulation results are further provided to demonstrate the validity of the derived approximated average bit error rate.

Keywords: free-space optical; intensity modulation with direct detection; channel state information; maximum likelihood sequence detection

1. Introduction

Optical wireless communication refers to the transmission of data in an unguided propagation media through the use of optical carriers [1–5]. Optical wireless communications (OWCs) can be divided into five categories; ultra-short range OWC, short-range OWC, medium range OWC, long-range OWC and ultra-long range OWC [1,2,4]. Long range OWC systems are referred to as Free Space Optical (FSO), which is the OWC used between buildings [1,2,4].

Free-space optical (FSO) communications have recently been adopted due to its high data rate (up to 10 Gbps), large bandwidth, transmission distance up to several kilometers, frequency above 300 GHz, which is a license-free spectrum, easily and quickly deployed and finally, reinstallation capability of the system [1–4,6].

The FSO challenges include atmospheric attenuation such as snow, dust, fog and rain, atmospheric turbulence, beam divergence loss, ambient light, misalignment and complexity of the system [1–4,7–10]. Due to the complexity generated from phase and frequency modulation and due to the high implementation cost, on-off keying (OOK) intensity modulation with direct detection (IM/DD) is implemented within the most current commercial FSO systems [11–16].

To evaluate the atmospheric turbulence effect, two methods were used. The first method is the Channel State Information (CSI) method, where pilot signals were sent to detect the channel condition [7,13]. For the mentioned systems, the receiver would require knowledge of the CSI to adjust the detection threshold [17]. To increase the bandwidth efficiency of FSO channels and to decrease the complexity, the second method was introduced in [13,17–19]. The second method is the blind detection method. The blind detection does not use pilot signals. It decreases the complexity of the receiver and increases the throughput [7,13].

A blind practical method for detecting wireless optical communication was introduced in [18]. In [20], the authors proposed an iterative sequence detector based on [18]. Due to the Bit Error Rate (BER) in [18,20] being floored for a small size observation window, the authors of [7] introduced an improved data detection methodology. This methodology, introduced in [7], used the specification of channel probability density function (PDF) and proposed a new algorithm that decreased the error floor. The authors of [13] have also derived an analytical expression of a conditional BER of the system proposed on [18]; however, the average BER was not derived.

One of the mitigation techniques used for the atmospheric turbulence effect and path loss attenuation is the assisted relay technique [2,6]. The assisted relay technique helps in shortening the hops, and thus, improving the performance significantly [2,6].

Table 1 accommodates some of the key pros and cons of the previous literature that used the blind detection method with FSO communication systems.

Table 1. Pros and cons of Free-space optical (FSO) blind detection papers in the literature.

Reference Number	Pros	Cons
[7]	Novel data detection methodology	No mathematical model
[13]	Two decision steps	Monte Carlo simulations is missing
[15]	Gamma-gamma channel which covers moderate to strong range of atmospheric turbulence	Missing of weak turbulence regime
[16]	Proposed data efficient channel estimation method	Single iteration method
[18]	Two decision steps	No closed form equation

In this paper, we employed a blind detection method for a serial decode and forward relay of the FSO system over a log-normal channel. The novelty of this work is as follows:

- The combined advantages of blind detection and assisted relays motivated the research group to investigate the combined system in more details.
- Approximated average BER, which was not derived earlier in [7,13], is derived within the paper. Although the derivation of the analytical model is more difficult than the Monte Carlo simulation, it allows a better understanding of the proposed system and an easier comparison between the proposed model and other ones.
- The Monte Carlo simulation verifies the correctness of the derived expression.
- The obtained results show the closeness of the employed method using small windows compared with channel state information.
- The new results would promote the use of blind detection for more applications.

The remainder of this paper is organized as follows. Section 2 describes the system model. Section 3 presents our derived closed-form error probability for blind OOK detection. Our numerical results and discussions are presented in Section 4. Section 5 is devoted to the main conclusions.

2. System Model

An FSO system with IM/DD and OOK modulation is considered. The received signal of hop i, $r_i[k]$ in any discrete time k is

$$r_i[k] = h\, s_i[k] + n_i[k] \tag{1}$$

where $s_i[k] \in \{0, 1\}$, is the transmitted OOK symbol and $n_i[k]$ is the signal-independent additive white Gaussian noise with zero mean and variance $\sigma_n^2 = N_0/2$. The channel coefficient can be formulated as $h = h_l h_a$, where fading coefficient h_a, is the time-varying channel state due to atmospheric turbulence and is considered to be constant over a large number of transmitted bits. h_l is the channel attenuation.

The average electrical signal to noise ratio (SNR) is defined as $E[|s[k]h|^2]/N_0$, where $E[.]$ denotes the statistical expectation. The proposed system uses a single decode and a forward relay. The relay would help to shorten the communication link as shown in Figure 1. The impact of the decrease of the link length would significantly reduce the turbulence effect and path loss.

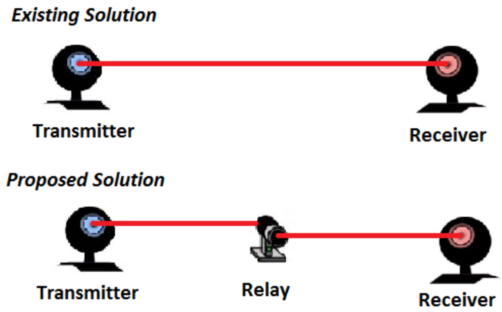

Figure 1. Synoptic diagram of the proposed blind detection free-space optical (FSO) system.

2.1. Channel Model

A log-normal channel for both weak and moderate turbulence is used. The log-normal distribution for the channel coefficient is defined as [14]

$$f_{LN}(h_a) = \frac{1}{h_a\sqrt{8\pi\sigma_x^2}} \exp\left(-\frac{(\ln(h_a) - 2\mu_x)^2}{8\sigma_x^2}\right),\ h_a > 0 \tag{2}$$

with $h_a = \exp(2x)$, where x is normally distributed random variable with mean μ_x and variance σ_x^2. The channel attenuation can be modeled as [13]

$$h_l = \frac{A_r}{\pi\left(\frac{\theta\, d_0}{2}\right)^2} \exp(-\beta_0 d_0) \tag{3}$$

where A_r is the aperture area, θ is divergence angle, d_0 is the distance between the transmitter and the receiver and β_0 is extinction coefficient.

2.2. Data Detection

2.2.1. For Perfect CSI

For a receiver with perfect CSI, the maximum likelihood (ML) decision rule for the kth bit and the optimum threshold are defined, respectively, as in [13]:

$$\left(r[k] - \frac{h}{2}\right) > 0;\ \hat{s}[k] = 1 \tag{4}$$

$$\left(r[k] - \frac{h}{2}\right) < 0;\ \hat{s}[k] = 0 \tag{5}$$

where $\hat{s}[k]$ is the detected bit.

2.2.2. For Blind Data Detection

To estimate the channel, the two-stage block by block receiver is performed:

$$\tau_1 = \frac{1}{L}\sum_{K=1}^{L} r[k] \tag{6}$$

where τ_1 is the first threshold used for the first step, and L is the observation window. Using the threshold, the first step of blind detection is:

$$r[k] > \tau_1;\ s'[k] = 1 \tag{7}$$

$$r[k] < \tau_1;\ s'[k] = 0 \tag{8}$$

where $s'[k]$ is the first step of decision for $s[k]$.

The second stage is performed as in [13] with the simplified form introduced in [7]

$$\tau_2 = \frac{1}{M'}\sum_{K=1}^{L} r[k]s'[k] \tag{9}$$

where

$$M' = \sum_{K=1}^{L} s'[k] \tag{10}$$

which would result in

$$r[k] > \tau_2;\ s''[k] = 1 \tag{11}$$

$$r[k] < \tau_2;\ s''[k] = 0 \tag{12}$$

where $s''[k]$ is the second step of decision for $s[k]$.

In the proposed system, using the relay technique, stages one and two are performed at the relay and at the destination.

3. Derivation of Closed Form Average BER Expression

In this section, the equations used for calculating the average BER of the proposed scheme over the log-normal channel are discussed. The derivation of the average BER allowed us a better understanding of the proposed system, reduced long simulation time and an eased the comparison between the proposed model and other ones.

Average BER for Log-Normal Channel

The average BER of the proposed scheme is defined as in [13]:

$$ABER = \int_0^{\infty} P(e/L,h) f_h(h)dh \tag{13}$$

where the $P(e/L,h)$ is defined as in [13]:

$$P(e/L,h) \approx \frac{1}{2^L}\left(1+\sum_{M=1}^{L-1}\binom{L}{M}\frac{M}{L}P(e/L,M,h)\right) \tag{14}$$

where $\binom{L}{M}$ is the number of combinations of M items out of L.

$P(e/L,M,h)$ is defined as in [13]:

$$P(e/L,M,h) = Q\left(\frac{h}{\sqrt{2N_0+\frac{N_0}{2M}+\frac{N_0}{2(L-M)}}}\right) \tag{15}$$

where $M = \sum_{K=1}^{L} s[k]$ is the number of ones in the observation window with length L.

The Gaussian Q function is [21]:

$$Q(y) = \frac{1}{\pi}\int_0^{\pi/2}\exp\left(-\frac{y^2}{2\sin^2\theta}\right)d\theta \tag{16}$$

The PDF of the fading coefficient, h, which is given as $h = h_l h_a$:

$$f_{LN}(h) = \frac{1}{h\sqrt{8\pi\sigma_x^2}}\exp\left(-\frac{\left(\ln(\frac{h}{h_l})-2\mu_x\right)^2}{8\sigma_x^2}\right) \tag{17}$$

Substituting (14) and (17) in (13), we get:

$$\begin{aligned} ABER &= \tfrac{1}{2^L}\left(1+\sum_{M=1}^{L-1}\binom{L}{M}\tfrac{M}{L}\right) \\ &\times \int_0^\infty Q\left(\frac{h}{\sqrt{2N_0+\frac{N_0}{2M}+\frac{N_0}{2(L-M)}}}\right)\frac{1}{h\sqrt{8\pi\sigma_x{}^2}}\exp\left(-\frac{\left(\ln(\frac{h}{h_l})-2\mu_x\right)^2}{8\sigma x^2}\right)dh \end{aligned} \tag{18}$$

Making the change of variables:

$$x = \frac{\ln(\frac{h}{h_l})-2\mu_x}{\sqrt{8\sigma_x{}^2}} \tag{19}$$

This results in:

$$ABER = \int_{-\infty}^{\infty}\frac{1}{2^L\sqrt{\pi}}\left(\left(1+\sum_{M=1}^{L-1}\binom{L}{M}\frac{M}{L}\right)Q\left(\frac{h_l\exp(x\sqrt{8\sigma_x{}^2}+2\mu_x)}{\sqrt{2N_0+\frac{N_0}{2M}+\frac{N_0}{2(L-M)}}}\right)\exp\left(-x^2\right)dx\right) \tag{20}$$

This integration in (20) could be solved using Hermite polynomial approximation [22]:

$$\int_{-\infty}^{\infty}\exp(-x^2)f(x_i)dx \approx \sum_{i=1}^{n} w_i.f(x_i) \tag{21}$$

where w_i and x_i are the weights and the roots of the Hermite polynomial of order n, respectively.

Applying Equation (21) on Equation (20) yields:

$$ABER \leq \frac{1}{2^L\sqrt{\pi}}\left(1+\sum_{M=1}^{L-1}\left(\begin{array}{c} L \\ M \end{array}\right)\frac{M}{L}Q\left(\frac{h_l\exp(x\sqrt{8\sigma_x{}^2}+2\mu_x)}{\sqrt{2N_0+\frac{N_0}{2M}+\frac{N_0}{2(L-M)}}}\right)\right) \quad (22)$$

For the dual hop system proposed, an approximated average bit error rate (ABER) is calculated [23]:

$$ABER \leq \frac{1}{2}\left[\ 1-(1-2ABER_1)(1-2ABER_2)\ \right] \quad (23)$$

where $ABER_1$ and $ABER_2$ are the ABER for the first and second node, respectively.

4. Numerical Results and Discussion

In the obtained simulation results, 10^8 bits were transmitted for each depicted SNR value and the Hermite polynomial order was $n \leq 50$.

Now, we evaluate the ABER performance of the dual hop blind detection FSO system for various locations of the relay. The ABER performance was calculated over weak and moderate turbulence in order to investigate the degradation effects. The direct link simulation results, investigated in [13], were used as a benchmark to show the performance difference between the direct link and the proposed model. For the direct link, the power value was multiplied by two to achieve a fair comparison [6]. Table 2 shows the system parameters under investigation. Table 3 shows the standard deviation values with the multiple scenarios under weak and moderate atmospheric turbulence.

Table 2. System configuration.

Symbol	Value
A_r	$2\pi(0.1)^2$
β_0	$0.1\ \text{km}^{-1}$
C_n^2	$0.5\times10^{-14}\text{m}^{-2/3}$ $2\times10^{-14}\text{m}^{-2/3}$
d_0	1 km
θ	1 mrad

Table 3. Standard deviation values.

Atmospheric Turbulence	Link Type	Standard Deviation of the First Hop	Standard Deviation of the Second Hop
Weak Turbulence	Direct	0.1572	
	Dual-hop 500-500	0.0833	0.0833
	Dual-hop 600-400	0.0984	0.0679
	Dual-hop 400-600	0.0679	0.0984
Moderate Turbulence	Direct	0.3145	
	Dual-hop 500-500	0.1666	0.1666
	Dual-hop 600-400	0.196	0.1358
	Dual-hop 400-600	0.1358	0.196

The derived analytical results were verified with Monte Carlo simulations. Figures 2–4 show the weak turbulence. Figure 5 shows the combined analytical values for moderate turbulence. Figures 2–5 show that the ABER decreased when a relay is added due to decreasing the distance. When comparing the figures with weak turbulence, Figure 2 with Figures 3 and 4, it can be seen that the best location for the relay is in the middle of the channel. We have tried all the ranges for the relay, which showed that the equidistant relay is the best location. Figure 5 shows that the best location for the relay for moderate turbulence is also in the middle of the channel.

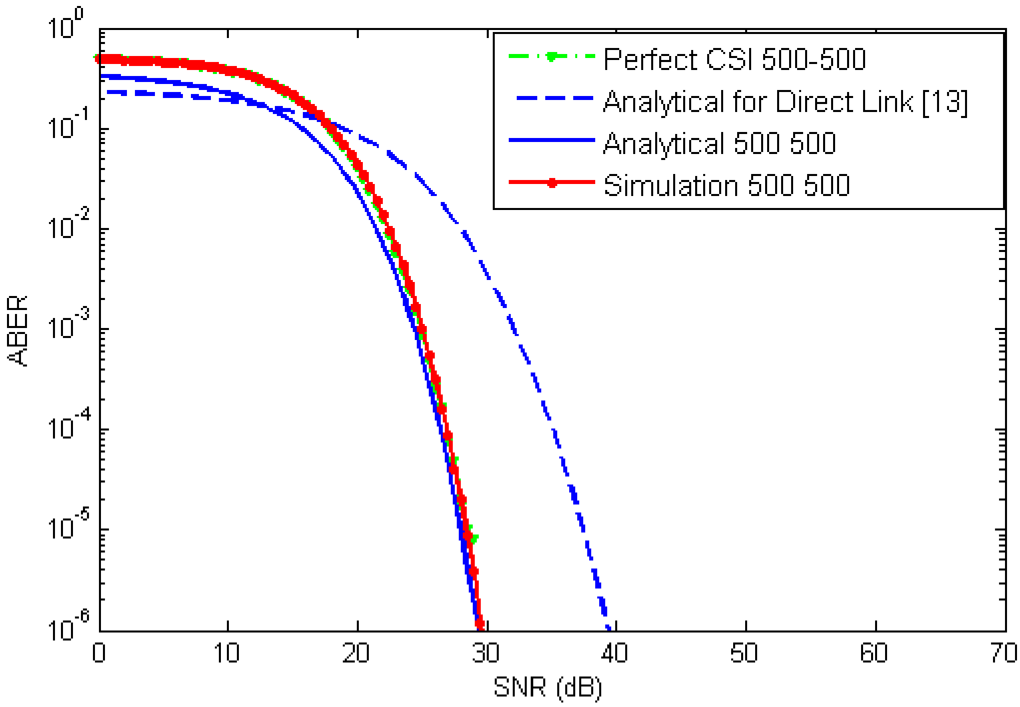

Figure 2. ABER performance for the direct link and a single equidistant relay, over weak turbulence.

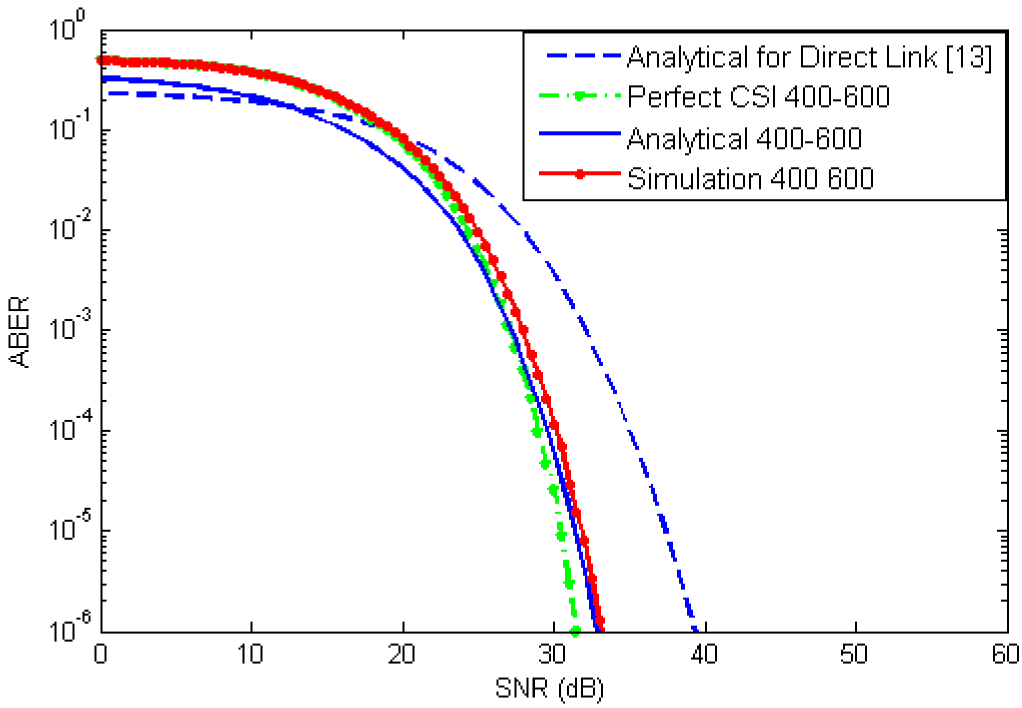

Figure 3. ABER performance for the direct link and a single relay after 400 m from the source, over weak turbulence.

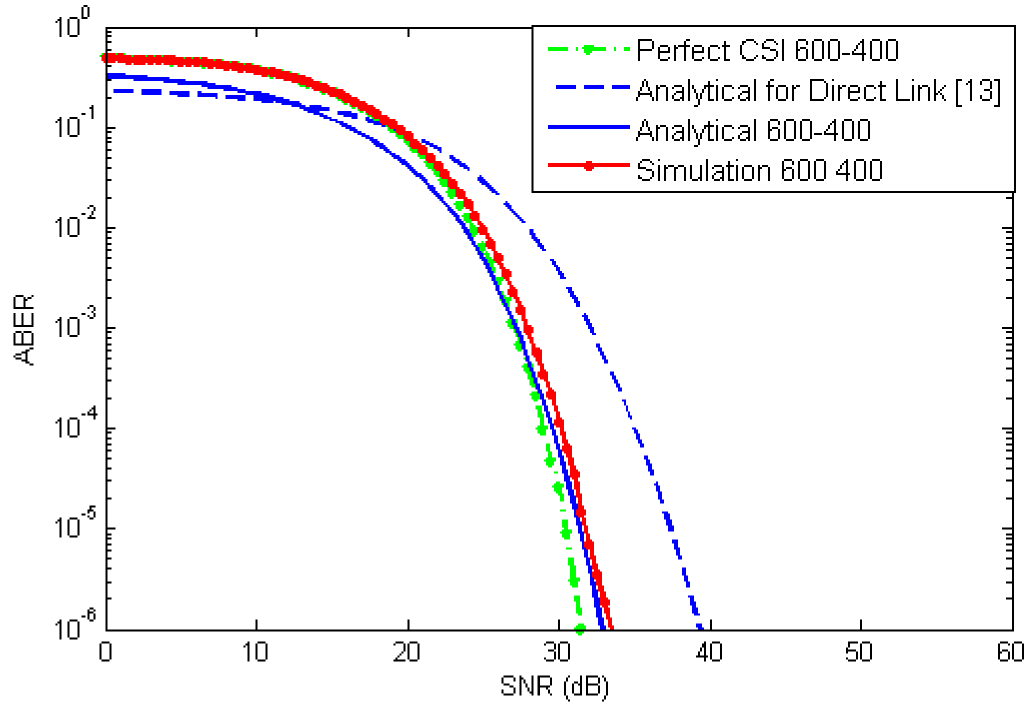

Figure 4. ABER performance for the direct link and a single relay after 600 m from the source, over weak turbulence.

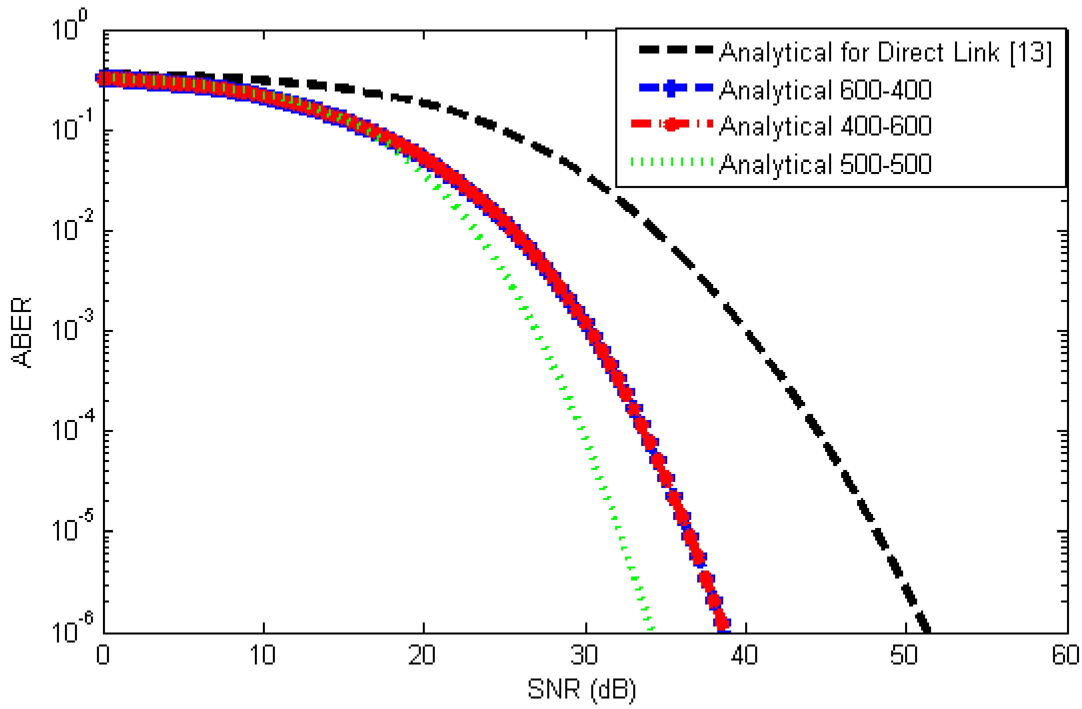

Figure 5. ABER performance for the direct link and a single relay with different locations, over moderate turbulence.

The generated analytical results are comparable to the CSI results as shown in Figures 2–4. The generated simulation results show the accuracy of the analytical results in Figures 2–4. Figure 2 shows an enhancement of around 10 dB between the direct link and using the relay.

Figures 3 and 4 also show an improvement of the proposed relay system by 6 dB. Figure 2 shows the equidistant relay outperforms its counterparts in Figures 3 and 4 by 3.5 dB.

As for the moderate turbulence, shown in Figure 5, an enhancement of 17 dB between the direct link and the equidistant relay can be seen. An enhancement of 12.5 dB was also obtained between the direct link and the other relays (600 m–400 m and 400 m–600 m).

5. Conclusions

A novel ABER performance analysis of a dual-hop blind detection FSO system was derived in this paper over a log-normal channel. Our Monte Carlo simulation results verified the validity of the theoretical predictions. Blind detection results were close to the CSI results while using a small window of length 32. Simulation results also showed that the proposed relay technique achieves better performance as compared to the results of a direct link, without a relay. It is worth to mention that as per the simulations, the equidistant relay is the optimum relay location. Additionally, the simulation results showed that even a non-equidistant relay would have a better performance than a direct link.

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