



Design of a high-speed data transmission link using free-space optics communication technology for metropolitan information networks

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Abstract. This paper describes the design and simulation of a high-speed data transmission link based on free-space optical communication (FSO) technology, motivated by the need for quick, cost-effective and high bandwidth solutions for metropolitan information networks. The proposed design helps to deal with unique characteristics of metropolitan information networks which are high node density with challenging physical infrastructures, high bandwidth connectivity demands at short to medium transmission distances, high atmospheric turbulence due to air pollution, smog, and building motion caused by transportation and construction activities. In the paper, key system parameters including receiver aperture diameter, transmitter beam divergence, electrical filter cut-off frequency, transmitted power and various environmental conditions are considered simultaneously to provide a design solution with a higher adaptability to channel instability due to high atmospheric turbulence and infrastructure constraints of urban area. The Q-factor is used as a quality criterion to evaluate through out the simulation and analyze of the system performance. For the data rate as high as 20 Gb/s of this study, the proposed FSO system design is ideal for scenarios that require short to medium-range high-speed links (up to 4 km) and under moderate weather conditions (visibility ≥ 2 km).

Keywords: Free-space optical communications, metropolitan information networks, optical communication design, free-space optics

1 Introduction

Free-space optics (FSO) communications, a long-range wireless optical communication technology using laser beams, has received considerable attention due to its ability to quickly establish in complex terrains such as mountainous areas, river-crossed regions or crowded urban zones with skyscrapers [1, 2]. This research field has become more important since the number of mobile devices have increased exponentially and bandwidth needs, which sometimes surpass the capacity of traditional mobile communication networks, leading to congestion and quality of

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service (QoS) degradation [3]. Especially, in large cities where the demand for broadband connectivity is increasing to support next-generation mobile communications, cloud computing, the Internet of Things (IoT) and the rapid growth of artificial intelligence (AI) based applications that process massive datasets like Google Cloud AI, Microsoft Azure AI, ChatGPT, DeepSeek, etc., FSO technology is being considered as a promising solution [4, 5, 6]. The use of wireless communication links based on laser transmission could effectively reduce the traffic pressure from metropolitan area networks (MANs) by establishing direct and low-cost connections between the core and edge networks, which could be co-existent with present information and sensing networks [7]. FSO systems are especially useful in metropolitan areas with dense, high-rise infrastructure where optical fiber deployment is technically difficult [8]. FSO also provides higher security than traditional radio frequency (RF) communication systems because it uses a line-of-sight (LoS) transmission mechanism that keeps the optical beam in a narrow path, allowing only receivers positioned within the beam's footprint to detect the signal [9, 10]. As a result, this transmission mechanism is ideal for creating secure private networks for defense, military operations and high-security applications. Furthermore, this technology also helps preserve radio frequency resources for both service providers and end users. Unlike RF communication which is strictly regulated by national radio frequency laws for frequencies below 3 THz, FSO operates in the infrared (IR) band at frequencies of hundreds of THz (for example, 193.4 THz). This allows FSO to be deployed flexibly without causing interference with the existing RF systems [11, 12]. In summary, FSO technology enables the deployment of high-speed communication links (up to tens of Gbit/s), with rapid setup, high efficiency and significantly lower cost than fiber-optic installations, making it a suitable solution for modern urban communication infrastructures [6, 13].

Important characteristics of metropolitan information networks should be considered for the design of FSO links include high node density with challenging physical infrastructures, high bandwidth connectivity demands at short to medium transmission distances, high atmospheric turbulence due to air pollution, smog, and building motion caused by transportation and construction activities [14, 15, 16]. These characteristics place challenges in developing a high data rate, yet cost-effective FSO links while being capable of mitigating effect of atmospheric and environmental conditions for deployment in urban networks. Previous researches have revealed several key parameters that impact system performance of FSO links, including the receiver aperture diameter, the divergence angle of the transmitter beam, the cut-off frequency of the electrical filter at the receiver, atmospheric channel conditions and transmitted optical power [14, 15, 16]. As a result, optimizing these design parameters is necessary to maintain reliable system performance under a variety of operating situations. First, the aperture diameter of the optical receiver and the divergence angle of the transmitter beam are important design parameters. Studies have shown that increasing the receiver aperture can improve signal reception and system performance during data transmission [17, 18, 19, 20] while beam divergence significantly

affects the signal focus and intensity, especially in long-distance transmission [21, 22, 23, 24]. Well designing the optical receiver aperture and the beam divergence could help to reduce the impact of atmospheric turbulence and misalignment due to building motion in urban areas. Second, the cut-off frequency of the electrical filter at the receiver is another critical factor. Since it regulates the bandwidth and power of the detected signal, it impacts the signal to noise ratio (SNR) and the total data throughput of the FSO link [25, 26]. Therefore, optimizing this parameter is necessary to maximize system performance in various conditions. Furthermore, FSO systems must deal with a variety of weather conditions, including turbulence, fog or rain. These situations might result in signal attenuation and instability. To overcome these problems, advanced modulation methods and adaptive optics have been proposed to improve transmission quality and maintain signal quality [15, 27, 28, 29]. Finally, the transmitted optical power is an important parameter that affects both the communication range and the system reliability. Higher transmission power can compensate for environmental losses and improve overall system performance. On the other hand, a high transmitted power causes an increase in the power consumption of the FSO system and might be hazardous for aviation activities and surrounding environment [26, 30]. As a result, the relationship between transmission power and received signal quality in association with the receiver aperture and transmitter beam divergence settings is a vital consideration for designing robust and efficient FSO systems.

Although the aforementioned parameters have been carefully investigated in the literature, few studies have systematically considered different design parameters in the same metropolitan network scenario. This paper fills that gap by thoroughly optimizing the key system characteristics, taking into account the technical and environmental challenges for urban FSO deployment. Based on the previous review of key design parameters, in this paper, we present a study on the design and simulation-based evaluation of a high-speed FSO communication system with various configurations tailored for urban network applications. Particularly, the impact of the key design parameters including antenna aperture, beam divergence and cut-off frequency of the receiver for metropolitan network conditions are studied for a design of high data rate FSO link at 20 Gb/s while considering urban-specific environmental effects such as pollution and turbulence through FSO channel visibility. The goal is to contribute to the development of next-generation communication infrastructures for metropolitan information networks. The remainder of the paper are organized as follows: The system model and description are explained in Section 2. Section 3 presents the simulation results and discusses how the design parameters impact system performance. Finally, in Section 4, we conclude the paper and point out the objectives for further research.

2 Design of FSO communication system for urban network

2.1 System Principle

Fig. 1 shows a full-duplex architecture of the free-space optical (FSO) communication system, including two transmission paths: the uplink and the downlink. Both links use transceiver modules with similar designs. Each transmission path consists of several main components owning specific functionality, as described below:

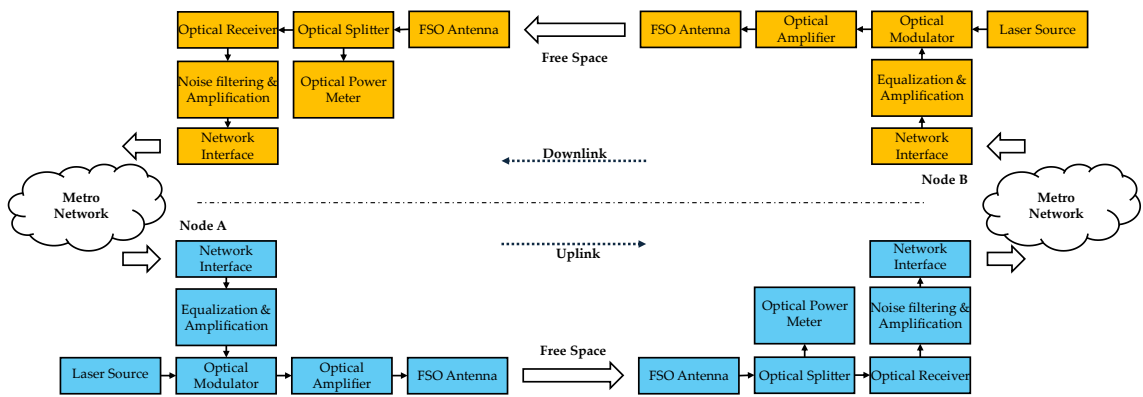


Fig. 1. Schematic diagram of the full-duplex FSO transmission system for metropolitan network

First, input data from metro network is connected to the link through a network interface to adapt with different connection standards. The data in form of electrical signals is then amplified to achieve an acceptable power for the electro-optical modulation process while also limiting signal distortion caused by the device's nonlinear properties. Next, the signal is converted to optical signal by an optical modulator with a wavelength range of 780 nm to 1600 nm from a laser source. Before propagating across the free-space channel, the optical signal is amplified by an optical amplifier to achieve the desired power level before being transmitted via the FSO antenna. This antenna focuses and guides the optical signal through the free-space, providing efficient reception. It is worth noting that the signal still can be coupled into an optical fiber if necessary.

When the optical signal arrives at the receiver, it is split into two parts by an optical splitter: a small portion (about 10%) is directed to an optical power meter to monitor the quality of the FSO channel while the other part (90%) is amplified by an optical amplifier to compensate for the FSO propagation attenuation. However, the amplification level must be carefully monitored to avoid damaging the optical receiver. After the amplification, the photodetector converts the optical signal back to electrical form. The resulting signal is then filtered to remove out-of-band noise and amplified to the appropriate level before being transmitted to the network interface for metro network.

The proposed design approach differs from the previous works which typically consider system parameters separately. In this work, we consider key system parameters simultaneously, including receiver aperture diameter, transmitter beam divergence, electrical filter cut-off frequency, transmitted power and various environmental conditions. This overall optimization strategy is particularly well suited for dynamic metropolitan network scenarios where design factors such as performance and system cost should be considered at the same time under the need for high data rate connectivity demands. This design approach would allow a higher adaptability to channel instability due to high atmospheric turbulence and infrastructure constraints of urban area. However, the current approach does not yet include adaptive real-time tuning, which has been identified as an area for the future studies. Furthermore, the simulation scenarios assume clear line-of-sight (LoS) conditions, so practical deployments may necessitate additional alignment mechanisms to ensure consistent operation.

2.2 System configuration and simulation

Fig. 2 illustrates the design and simulation schematic of a FSO communication link under various transceiver/channel conditions and transmission distances. This system is built upon the general architecture shown in Fig. 1, which includes main functional blocks for reliable demonstrating of the optical signal transmission and reception process.

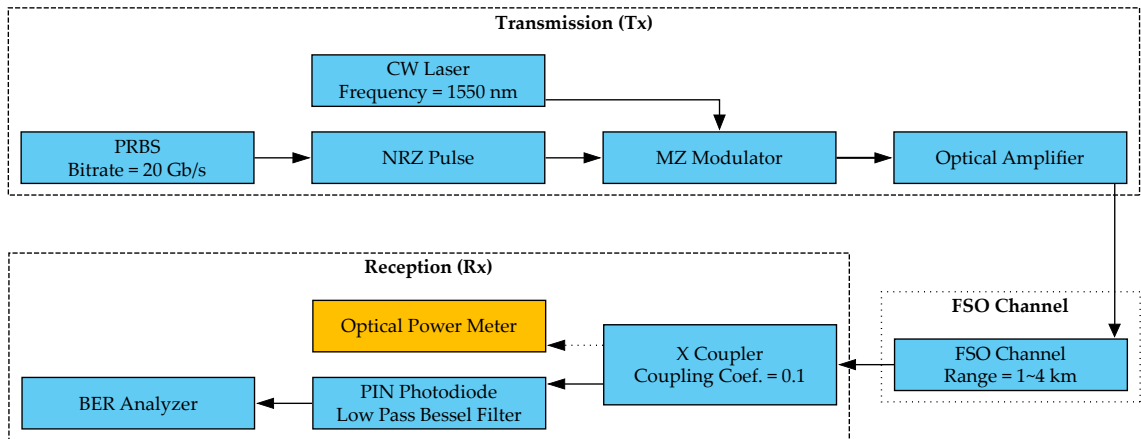


Fig. 2. System configuration of the designed FSO system link

At the transmission side, the input signal is first generated at the data rate of 20 Gb/s using a pseudorandom binary sequence (PRBS) generator before being mapped to non-return to zero (NRZ) format by a pulse pattern generator. For generating the optical carrier, we use a continuous wave (CW) laser with a wavelength of 1550 nm and the output power varies depending on simulation scenarios. A Mach-Zehnder modulator (MZM) is used to modulate the data into an optical signal. After the modulation, the signal is amplified by an optical amplifier with an

adjustable gain to achieve a suitable signal power level before transmission through the FSO channel.

At the receiver, after propagating through the free-space channel, the optical signal is split into two parts by an optical splitter. Here, the small part (10% of the signal power) is used for monitoring the channel quality and the remaining part is guided to a PIN photodiode to convert the received optical signal into electrical signal. To eliminate out-of-band noise components, the signal is passed through a Bessel low-pass filter (LPF) with an optimized cutoff frequency. Finally, the system performance is evaluated through a Q-factor/BER analyzer. The simulation system parameters are described below in Table 1.

Table 1. Simulation parameters for FSO system using OptiSystem 14

Parameter	Symbol / Unit	Value / Range	Description
Data rate	R (Gb/s)	20	Transmission bit rate of the system
Wavelength of laser source	λ (nm)	1550	Central wavelength of CW laser
Transmitted optical power	P_{tx} (dBm)	0 to 20	Launch power of the transmitter
Receiver aperture diameter	D_r (cm)	14 - 24	Aperture size of the receiving antenna
Beam divergence	θ (mrad)	1.4 - 2.6	Divergence angle of transmitted beam
Transmission distance	L (km)	1 - 4	Length of the FSO link
Channel attenuation	α (dB/km)	4, 7, 10	Simulated atmospheric loss
Visibility	V (km)	0.9 - 2.6	Atmospheric visibility index
Electrical filter cut-off frequency	f_c (GHz)	6 - 12	Cut-off frequency of Bessel LPF
Optical amplifier gain	G (dB)	Variable	Compensation for channel losses

3 Results and discussion

In this section, performance of the FSO communication system is studied under various conditions the transceiver and the channel. These studies would offer a more accurate assessment on the performance and feasibility of FSO systems for metro network applications.

3.1 Evaluation criteria

To evaluate the system performance, we use Q-factor as the primary evaluation metric in this paper. Q-factor directly reflects the quality of the detected signal and is widely used in the analysis of high-speed free-space optical (FSO) communication systems [26, 29]. The Q-factor

measures the ratio of the desired signal levels to the noise, providing a reliable indicator of system performance. Although bit error rate (BER) is also a popular performance indicator, it can be calculated analytically using a standard Gaussian error function and the Q factor. As a result, we concentrate on analyzing the Q-factor in depth, as it adequately represents both signal integrity and reliability.

Basically, the Q-factor is determined as below:

$$Q = \frac{|S_1 - S_2|}{\sqrt{\frac{1}{2}(\sigma_1^2 + \sigma_2^2)}} \quad (1)$$

where S_1, S_2 represent the signal levels (0 and 1 in NRZ format) and σ_1, σ_2 are the standard deviations corresponding to levels S_1 and S_2 respectively.

Based on Q-factor, BER can be calculated as follow:

$$BER = \frac{1}{2} \operatorname{erfc}\left(\frac{Q}{\sqrt{2}}\right) \quad (2)$$

where $\operatorname{erfc}(\cdot)$ is the complementary error function of the Gaussian distribution.

3.2 Impact of aperture diameter of optical receiving antenna and beam divergence of optical transmitting antenna

During the studies, it is found that increasing the receiver aperture diameter improves signal quality and helps to detect optical signal more accurately and efficiently. Similarly, reducing the beam divergence of the transmitting beam gives better convergence which minimizes the dispersion and enhances transmission quality. However, choosing large receiver apertures or ultra-low divergence angles may cause problems related to the component size and system cost which may affect the feasibility and cost of the overall system.

The results shown in Fig. 3 and Fig. 4 illustrate the relation between the Q-factor and the receiver aperture diameter and the beam divergence angle, respectively. The FSO system is evaluated at data rate of 20 Gb/s, LOS distance of 2 km and attenuation coefficient of 7 dB/km. In Fig. 3, the simulations show that the Q-factor almost increases linearly as the receiver aperture diameter expands from 14 cm to 24 cm. This demonstrates that increasing the receiver aperture significantly improves signal reception, resulting in higher SNRs and better system performances. On the other hand, Fig. 4 demonstrates the relation between Q-factor and beam divergence. The results reveal that as beam divergence increases from 1.4 mrad to 2.6 mrad, Q-factor reduces sharply. This reduction is caused by the spread of beam energy which reduces the received signal power.

Based on these results, we can draw two important points for the FSO system design. First, increasing the receiver aperture diameter improves signal quality, especially under high-attenuation conditions. Second, minimizing beam divergence enhances signal reception at the

receiver, thereby stabilizing the system performance—particularly for high-speed configurations. However, larger receiver aperture increases the physical size of the receiver, while a smaller divergence angle demands stricter alignment and precision at the transmitter.

To balance the signal quality, the system dimensions and the cost, we select a receiver antenna aperture diameter of 20 cm and a transmitter beam divergence of 2 mrad for 20 Gb/s data rate FSO systems operating over a 2 km link with atmospheric attenuation of 7 dB/km. This configuration provides optimal signal quality while maintaining feasibility in terms of technical implementation and cost-effectiveness.

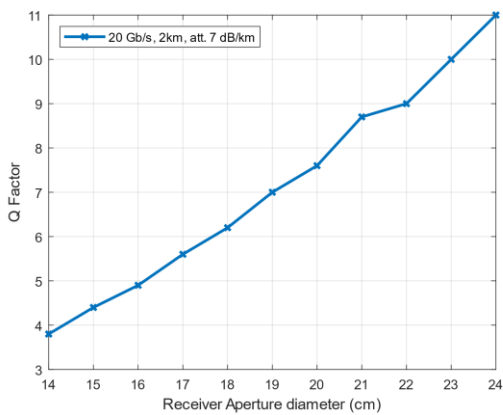


Fig. 3. System performance versus receiver aperture diameter

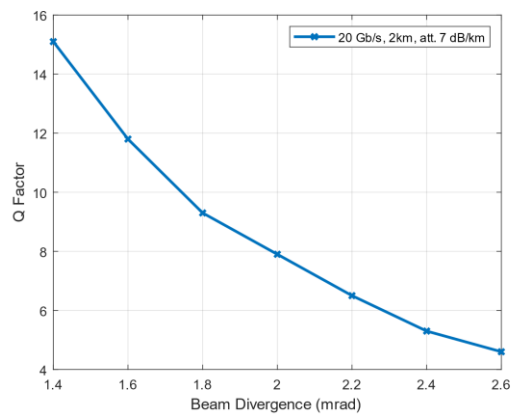


Fig. 4. System performance versus beam divergence of the transmitting antenna

3.3 Impact of the cut-off frequency of the electric filter at the receiver

This investigation aims to determine the optimal cut-off frequency for the electrical filter at the receiver. The electrical filter plays an important role in filtering the noise from the photodetector and other interference sources in the FSO channel. Fig. 5 illustrates the dependence of the Q-factor on the electrical filter’s cut-off frequency with system configurations proposed in Section 3.2.

The results indicate that, for a 20 Gb/s system, the Q-factor reaches a maximum of around 8.6 dB at a cut-off frequency of 10 GHz and gradually decreases when the frequency varies from this optimal point. As the cut-off frequency increases from 6 GHz to 10 GHz, the Q-factor improves considerably. The system performance reaches saturation and begins to degrade for the cut-off frequency larger 10 GHz. This tendency comes from the fact that when the cut-off frequency is lower than 10 GHz, the filter also mitigates the received signal, resulting in a reduced received signal power and a lower SNR. And when the cut-off frequency exceeds 11 GHz, the system experiences increased out-of-band noise, causing lower SNR and Q-factor. Therefore, choosing a suitable bandwidth may help avoid signal distortion while not allowing too much noise interfering to the signal.

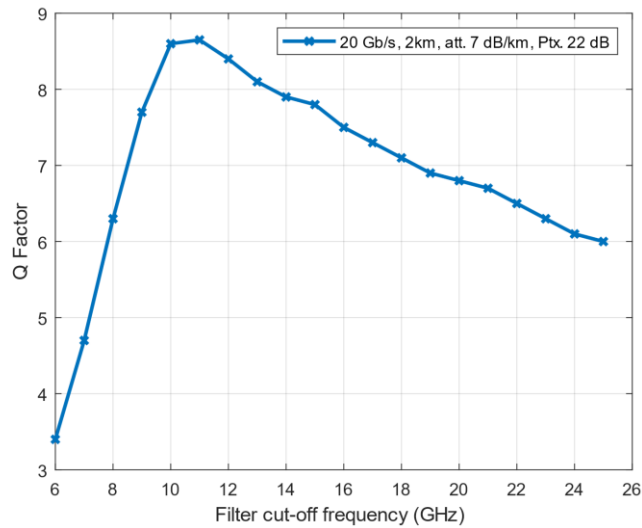


Fig. 5. System performance versus cut-off frequency of the receiver's electrical filter

As a result, for the 20 Gb/s system, it is desired that the filter cut-off frequency should be set around 10 GHz. This threshold may provide a balance between signal preservation and noise suppression for FSO systems with a moderate atmospheric attenuation of 7 dB/km and medium transmission distance of 2 km.

3.4 Impact of FSO transmission channel conditions

In this section, the paper studies and evaluates the FSO system's transmission capabilities under different channel parameters. Here, we use two factors, FSO propagation length and channel visibility, for the investigations. Channel visibility is an important characteristic that measures signal attenuation according to atmospheric conditions such as clouds, rain, humidity, air quality and so on. Note that the higher the visibility of the channel, the smaller its attenuation and vice versa. For the simulations, the transmission power at the transmitter (P_{tx}) is kept constant at 13 dBm and signal quality is determined at the receiver using the Q-factor.

Fig. 6 shows the Q-factor as a function of the free-space optical channel visibility for channel lengths ranging from 2 km to 4 km with step of 0.5 km. The results show that as the visibility increases (clearer atmosphere), the channel attenuation decreases, leading to a significant increase in the Q-factor for all channel lengths. The studies also indicate that for the same visibility, longer transmission channels have lower Q-factors, due to the higher total losses over the longer channel.

In practical system design, each channel length requires a minimum visibility value to ensure a Q-factor above 6 dB, corresponding to $BER \sim 10^{-9}$ which is an acceptable threshold in telecommunication systems. It can be seen from the results that to achieve $Q \geq 6$ dB for different

FSO link lengths, the minimum visibility required is around 1.8 km, 2.6 km, 3.6 km, 4.8 km and 6 km for the transmission distances of 2 km, 2.5 km, 3 km, 3.5 km and 4 km, respectively. To guarantee good transmission performance for FSO systems under different atmosphere conditions, it is important to select a suitable channel length that corresponds to the visibility environment in the deployment area. In addition, we may consider adding amplifiers or changing the transmission power to meet different channel conditions.

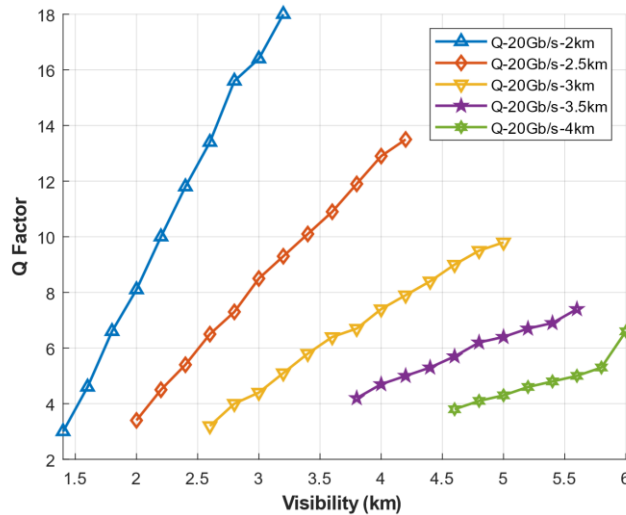


Fig. 6. System performance variation with transmission channel visibility for FSO links with changing lengths

3.5 Impact of the signal power transmitted to the FSO transmission channel

Finally, the study investigates the necessary power threshold for the system to reach a specific quality level at the measured bit rate. This is an important phase in the system design process before it can be used in practice, especially for FSO systems with poor atmospheric conditions as well as to extend working range. Here, we investigate three specific cases with different attenuation indexes:

Case 1: A channel with an attenuation of 4 dB/km (corresponding to a visibility of ~2 km), the system investigated at distances of 3 km and 4 km (Fig. 7).

Case 2: A channel with an attenuation of 7 dB/km (corresponding to a visibility of ~1.1 km), the system quality surveyed at distances of 2 km and 3 km (Fig. 8).

Case 3: A channel with an attenuation of 10 dB/km (visibility ~0.9 km), the system investigated at distances of 1 km and 2 km (Fig. 9).

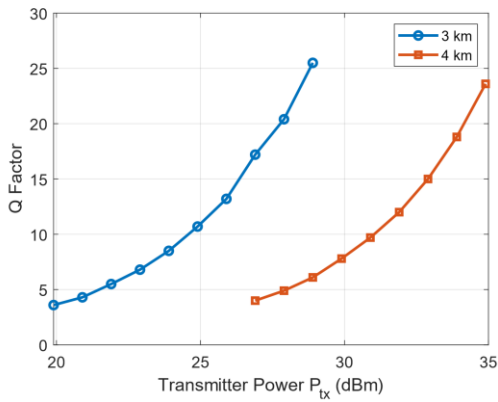


Fig. 7. System performance vs. power for a channel with distances of 3 km and 4 km and an attenuation of 4 dB/km

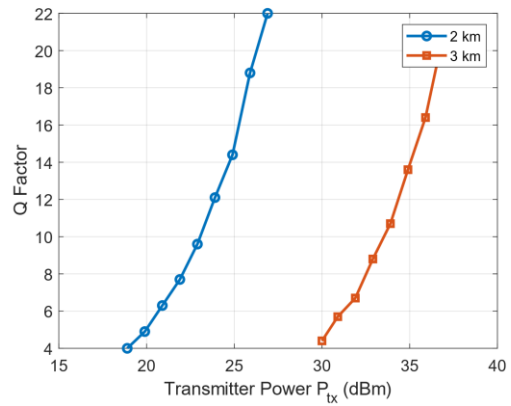


Fig. 8. System performance vs. power for a channel with distances of 2 km and 3 km and an attenuation of 7 dB/km

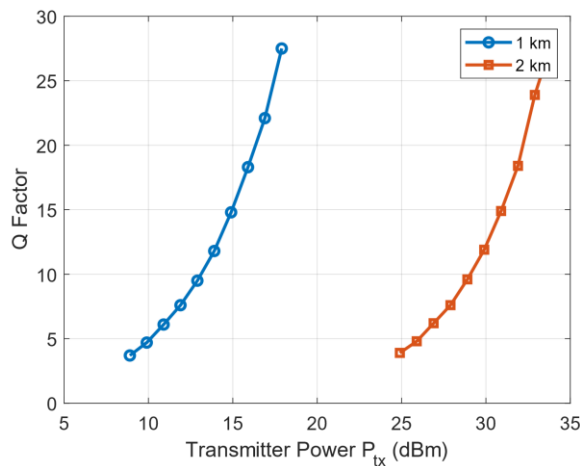


Fig. 9. System performance vs. power for a channel with distances of 1 km and 2 km and an attenuation of 10 dB/km

The results from Figs. 7-9 show that signal quality, evaluated through the Q-factor, increases significantly when the transmission power P_{tx} increases in all cases. It can also be seen that a considerable increase in power is required to compensate for the channel losses when the transmission distance becomes longer. For instance, for channels with low attenuation of 4 dB/km, when the distance is extended from 3 km to 4 km, the transmitted power needs to increase about 6 dB to maintain the same Q-factor (see Fig. 7). For channels with a moderate attenuation of 7 dB/km (see Fig. 8), an extra 10 dB of transmitted power is required to increase the distance from 2 to 3 km. As shown in Fig. 9, channels with high attenuation of 10 dB/km have a significant

impact on the signal under poor weather. In this scenario, increasing the transmission distance from 1 to 2 km required an increase by 16 dB for the transmitted power.

Therefore, for the system to maintain the same signal quality when the transmission distance increases, energy efficiency becomes an important element to consider. This is an important factor for designing high-speed FSO systems because the transmission channel is significantly affected from free-space propagation.

4 Conclusion

In today's high-density metro network applications with high data rate requirements, communication system design and optimization play an important role. This work describes the design, simulation and performance evaluation of a 20 Gb/s FSO link under various situations to suggest the most optimal set of parameters including antenna aperture, beam divergence, visibility, transmission distance and channel attenuation. For the data rate as high as 20 Gb/s of this study, the proposed FSO system design is ideal for urban metropolitan networks that require short to medium-range high-speed links (up to 4 km) under moderate weather conditions (visibility ≥ 2 km). However, it is less suitable for severer conditions with heavy fog, rain, or highly unstable atmospheric conditions in which signal attenuation exceeds 10 dB/km unless significant power amplification or adaptive optics are implemented with a trade for high power consumption and high cost. The simulation results show that the larger antenna aperture diameter greatly increases signal reception, raises the Q-factor. A reduced beam divergence also helps to focus energy, decreases scattering loss and enhances transmission performance. Furthermore, other factors such as the cutoff frequency of the electrical filter of the receiver, the visibility index of the environment and the transmitted power have a considerable impact on the signal quality and must be considered during the system design process. To achieve effective channel deployment, these aspects must be adapted within appropriate technical and economic perspectives. The results not only offer guidance for high-speed FSO system design, but may also be used to more complicated situations, such as those with changing atmospheric conditions.

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