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Investigations of Free Space Optical Communications Under Real-World Atmospheric Conditions

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Abstract

Due to the increasing demand for higher bandwidth in modern communication systems, conventional networks are continuously expanded with new technologies to improve coverage. Free space optical communications (FSOC) shows some significant advantages concerning system setup time in comparison with the classical fiber optical systems on one hand, substantial spectral bandwidth and performances in comparison with the wireless systems under certain conditions on the other hand. This makes this technology not only a reasonable extension for metropolitan area networks but also provides the capability to set up a network after an outage in case of natural disaster quickly. But transmitting data by using FSOC involves some limiting factors that have to be considered prior to each installation. Since the atmospheric channel is not static, the influence of changing weather conditions or industrial smog have a significant impact on the available bitrate. A simulation platform is developed and presented in this paper for investigation of FSOC considering these circumstances. Regarding the atmospheric channel, turbulence, distance-dependent beam divergence, and applied modulation schemes, a general overview of the capabilities is presented and discussed. The insight of this paper should help to make a decision under which preconditions either the FSOC provides a meaningful application possibility, or the limiting factors become too crucial and other technologies must be considered.

Keywords Free space optical communications · Attenuation · Scattering · Bit rate · Constellation diagrams

1 Introduction

Free space optical communication is a technology to transmit data by the propagation of infrared light in free space. Systems consist of an optical transceiver at both ends to provide bidirectional capability. The attempt is very similar to optical fiber communication

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systems, just without the need of a dedicated quartz glass optical fiber as transmission media. The technology itself is not new, but with the invention of laser diodes and highly sensitive photodiodes as well as sophisticated modulation schemes, it now meets the specifications for the rising demand of high bandwidth connections [1]. There are multiple applications where the advantages of free space optical communications (FSOC) can be utilized. Unlike the limited spectrum availability with radio frequency communication, optical communication has a license-free spectrum [2]. Since there is no fiber cable required, a connection can be established very flexibly and quickly with free visual contact or LoS (Line of Sight) between two points. This does not only enable quick connectivity after, e.g. natural disasters, but also a stable connection with moving objects like airplanes or even satellites. But the precondition for visual contact is also a downside. The transceivers always must be adjusted very precisely to prevent pointing errors. And even if this is the case, unpredicted obstacles or bad atmospheric conditions in the line of sight can still influence the signal quality negatively. The primary factors that deteriorate the link are absorption, scattering, and turbulence [3]. The given limitations narrow the use cases for free space optical communications in common commercial installations where a reliable connection is mostly mandatory. Due to the usage of point to point connections, scaling a network is more complex and requires additional maintanance for each connection. Because of the narrow laser beam, free space optical communications is much more secure than radio-frequency transmissions, but eavesdropping is still possible. Either by implementing a beam splitter close to the transmitter, or intercepting photons in the beam divergence area [4]. Additional encryption techniques in network layer or transport layer like IPsec or TLS/SSL are therefore recommended.

2 Free Space Optical Link System Model

The block diagram of a FSOC system contains three primary subsystems: transmitter, channel, and receiver [5].

Transmitter Its primary function is to modulate the incoming message signal onto the optical carrier which is then propagated through the atmosphere to the receiver. Essential components are the modulator, the optical source which is most likely a laser diode, and a transmitting telescope or optical antenna. The telescope is not only responsible for beam shaping but also the movable part for beam tracking (Fig. 1).

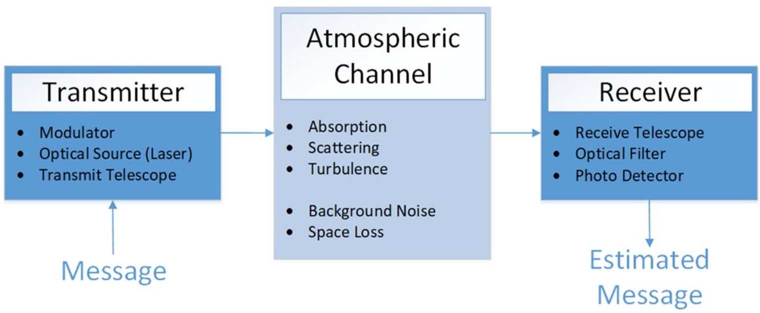


Fig. 1 Block diagram of free space optical communication systems

Channel The channel is a major limiting factor of FSOC since unpredictable conditions like snow, fog, rain, or clouds can influence the strength of the received signal. It is important to mention that these factors do not have fixed characteristics and change significantly with time.

Receiver It is used to recover the transmitted data. It consists of a receiver telescope which is the equivalent to the transmitter telescope, a very sharp optical bandpass filter to reduce the background noise and limit the received signal bandwidth, and the demodulator.

3 Channel Model with Different Factors

3.1 Atmospheric Channel

The selection of optical wavelengths depends on multiple factors. For terrestrial FSOC systems costs, eye safety, and the transmission windows are critical. Regarding eye safety regulations, 1.5 μm and above wavelengths are always the preferred option since wavelengths between 400 nm and 1400 nm are hazardous because they are focused directly within the human's eye on the retina [6]. The transmission windows arise from the radiation absorption of molecules in the atmosphere. Certain gases such as water, carbon dioxide or ozone absorb electromagnetic waves at a particular frequency. In contrast to these absorption bands, there are spectral areas with little or no absorption to specific wavelengths, these are known as atmospheric windows. These wavelengths are preferred for a low attenuation optical transmission [7]. Other limiting factors like scattering are also dependent on the wavelength. This is covered later in the paper.

3.2 Beam Divergence Loss

The most significant loss in FSOC is usually the beam divergence loss which describes the attenuation between two antennas. The divergence loss is dependent on propagating beam width and the diameter of the receiving telescope which can be noted as an equivalent to the antenna gain in radio transmission. It also depends on the propagating wavelength because of the inclusion of the free space loss. The formula for the calculation of the received power is:

$$P_R = P_T \cdot G_T \cdot G_R \cdot L_P \tag{1}$$

where L_P is the free space path loss, G_T and G_R the effective gain of receiver and transmitter, P_T the transmitted power and P_R the received power. The gain of both optical antennas or telescopes is approximated by:

$$G = \frac{(4\pi \cdot A)}{\lambda^2} \tag{2}$$

where λ is the wavelength of the transmitted signal and A the effective optical antenna area. Depending on the efficiency and optical antenna characteristics, the total gain can vary [7]. With this equation in mind, it can be said that a narrow beam divergence is preferable with the condition that the antennas are perfectly aligned. Otherwise active beam tracking and pointing systems are required to reduce the pointing loss that occurs when the center of the beam does not directly face the receiver. The free space loss factor is given by:

$$L_P = \left(\frac{\lambda}{4\pi R}\right)^2 \tag{3}$$

where R is the distance between both optical antennas.

3.3 Influence of Weather Conditions

As already mentioned in the introduction, the quality of an FSOC link can vary strongly depending on weather conditions that affect the line of sight. Mostly fog, rain, and snow decrease the received signal power. Additionally, attenuation must be considered. If the number of particles in the atmosphere reaches a certain threshold, a complete link outage can occur. For a theoretical approach, this effect is divided into three different ranges regarding the size of the particles. Fog consists of tiny particles that lead to Mie-scattering, in contrast raindrops and snowflakes are comparatively larger and produce deeper fades in the signal [8, 9]. The effect of fog can be calculated with the Mie-scattering theory which is very sophisticated and requires detailed fog parameters. Alternatively, an approach based on visibility range information can be used [10]. It defines the attenuation coefficient of fog given by an empirical model for Mie-scattering. The specific attenuation in dB/km is derived by $A(\mathrm{dB}/km) = 10\log_e[\gamma(\lambda)]$.

$$\gamma(\lambda) = \frac{3.91}{V}\left(\frac{\lambda}{550\,\mathrm{nm}}\right)^{-p} \tag{4}$$

where V stands for the visibility range and λ is the operating wavelength. p is the size distribution coefficient that describes the "thickness" of the fog. 550 nm is the reference wavelength used in this approach. The Kruse model [11] defines p for different visibility factors:

$$p = \begin{cases} 1.6, & V > 50 \\ 1.3, & 6 < V < 50 \\ 0.585V^{1/3}, & V < 6 \end{cases}$$

Unaffected by the visibility range, the attenuation factor for fog is always dependent on propagating wavelength. A larger wavelength leads to lower attenuation (Fig. 2).

Rain and snow attenuation are not affected by the propagating wavelength. The specific attenuation increases with the rainfall or snowfall rate.

3.4 Turbulence

Inhomogeneous temperature and pressure lead to various refractive index values in the atmosphere that directly influence the transmitted laser beam negatively. Turbulent cells are formed by these factors. These cells, also called eddies, have various sizes and different refractive indexes. Because these cells are distributed very randomly, calculating this influence is very sophisticated. When an optical signal is distributed through a turbulent atmosphere, it causes wave front distortion in phase and amplitude [12]. This can lead to a complete link failure. When the cells are larger than the beam size, a phenomen called beam wandering occurs. Due to the change of refractive indexes in the cells, the distribution angle of the beam changes (Fig. 3).

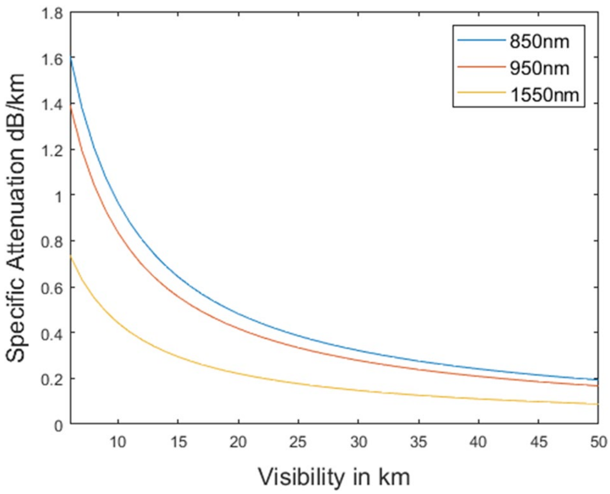


Fig. 2 Specific attenuation for fog depending on wavelength

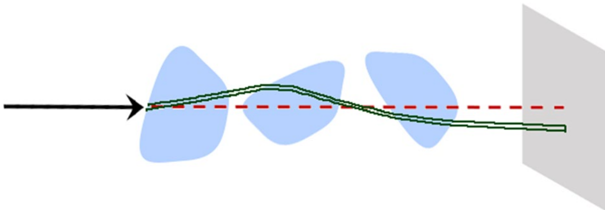


Fig. 3 Influence of turbulence cells on propagation angle

4 Simulation, Implementation, and Evaluation

To simulate a FSOC link under real-world conditions, different tools have been investigated with respect to the free space optical communications. After evaluating the feasibility of different simulation systems, it has been decided to use OptiSystem by Optiwave Systems Inc. for this project [13]. The user interface is very similar to Simulink. Systems are designed with building blocks that are connected with each other. The building block libraries in OptiSystem do not only contain different modulation techniques, but can also simulate the propagation of a laser beam in free space. It is possible to use the software for free with a 30-day evaluation license at universities. In this work two modulation schemes were used and studied: 16-QAM and DP-QPSK. Since the expected noise on an atmospheric channel is much larger than in an optical fiber, the utilized modulation schemes have rather low order, which will likely lead to a smaller Bit-Error-Rate at a given distance. The corresponding results of the propagation limitations were documented.

4.1 16-QAM

Figure 4, which is a screenshot of the OptiSystem model, gives an overview over the system architecture used in the realization of an optical communication system for the 16-QAM modulation scheme. The proposed architecture contains multiple components:

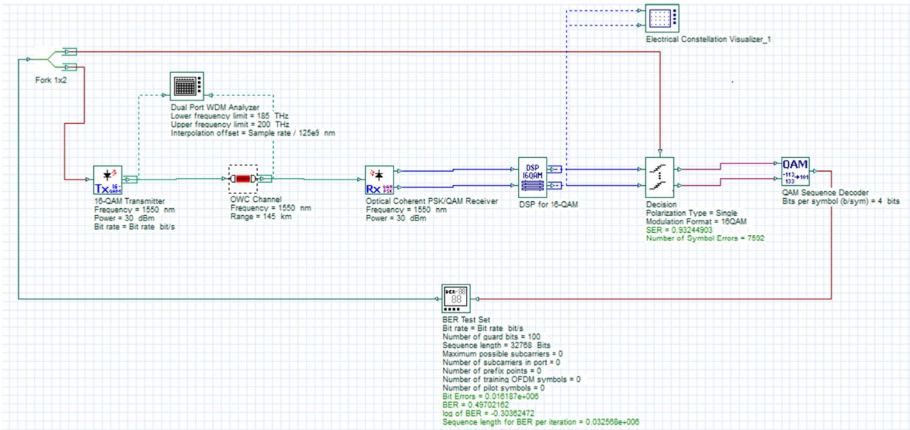


Fig. 4 Screenshot of the OptiSystem 16-QAM model

1. 16-QAM Optical transmitter: It transmits at 1550 nm with a power of 30 dBm. It is characterized with a 10 cm, 30 cm and 100 cm diameter aperture.
2. Transmission channel OWC: It models an optical wireless communication channel. It is in fact the simulation of the free space channel. In this project the attenuation characteristic is modified according to the weather conditions.
3. Optical coherent QAM receiver: It consists of a homodyne receiver which transforms the light into electrical power.
4. DSP for 16 QAM: It performs several functions to ensure the recovering of the incoming transmission channel after the coherent detections.
5. Decision: It processes the I and Q electrical signal channels received from the DSP component, normalizes the electrical amplitudes to the respective M-QAM grid and performs a decision on received symbols based on the presetting [8].
6. QAM sequence decoder: It decodes two parallel QAM-M-ary symbol sequences to a binary signal [8].
7. BER test set: It calculates the bit error rate by generating a large bit sequences, transmitting them to the DUT and then compares the transmitted sequence with the one received. Based on that the BER is determined.
8. Electrical constellation visualizer: Displays the in-phase and quadrature-phase electrical signals in a constellation diagram
9. WDM analyzer: It detects, calculates and visualizes the optical power, SNR, noise etc. for each channel. Since there's only one channel this analyzer still provides a good overview on effective attenuation behavior.

4.2 DP-QPSK

Figure 5, which is a screenshot of the OptiSystem model, gives an overview over the system architecture used in the realization of an optical communication system for the DP-QPSK modulation scheme. The used architecture contains almost the same components as the 16-QAM constellation with a difference in modulation and demodulation architecture. Therefore, the system description is not repeated at this point.

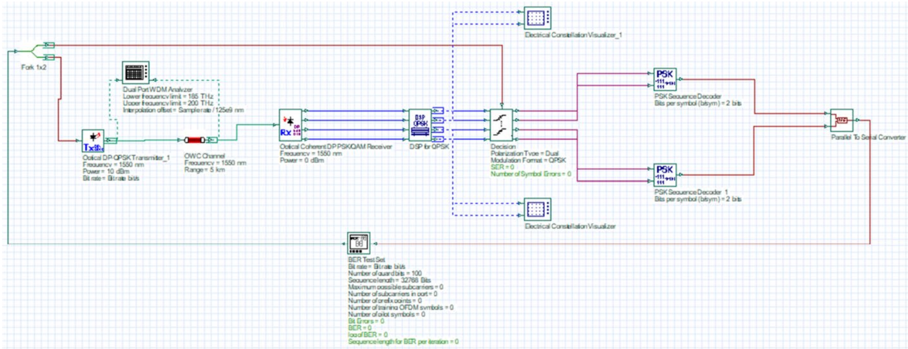


Fig. 5 Screenshot of the OptiSystem DP-QPSK model

4.3 Influence of Fog and the Transceiver Apertures

Different cases have been tested using the proposed system. Based on different weather conditions (clear sky, haze, fog etc.) and modifiable antenna aperture (10 cm, 30 cm, 100 cm), the bit error rate (BER) is calculated in a distance ranging from 0 km to 200 km. The diagrams are intentionally presented in linear scale to emphasize the possible transmission distances. Besides the attenuation through fog, conditions for this test case are ideal. Transceiver efficiency is set to 100%. For real-world conditions this should be set to around 80%. Also electrical noise is added to active parts of the circuit. The influence of scintillation is simulated by the optical channel. The bitrate is set to 10 Gbit/s.

4.4 10 cm Transceiver

Figure 6 shows the BER versus distance in different weather conditions with a 10 cm aperture size of both transmitter and receiver. It is remarkable that both techniques are almost identical. For low attenuation 0.4 dB/km the propagation is possible and the BER is acceptable up to approximately 100 km. After exceeding the 100 km range the reconstruction of the transmitted signal in the receiver side is no more feasible. For higher attenuation coefficients (4 dB/km, 21 dB/km) in bad weather circumstances, the transmission is achievable between 2–10 km but not above this range (Table 1). For the second test the antenna diameter of the transceiver is increased from 10 to 30 cm and then 1 m.

4.5 30 cm Transceiver

Figure 7 shows the BER versus distance in different weather conditions with a 30 cm antenna size of both transmitter and receiver. It is obvious according to the figure above

Table 1 Specific attenuation for different visibilities, derived with Kruse model

Clear sky	0.4 dB/km
Haze	4 dB/km
Fog	21 dB/km

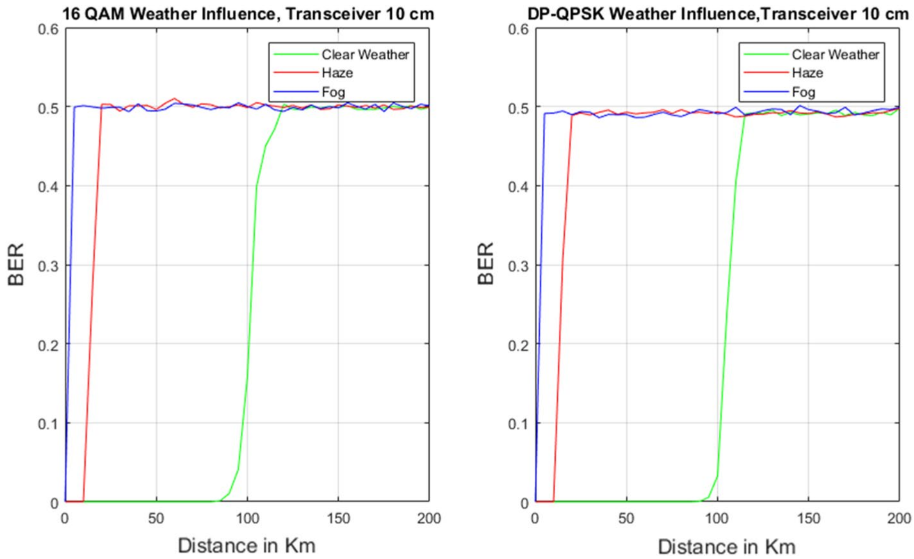


Fig. 6 BER showing the distance limit for clear weather, haze, and fog versus distance; transceiver aperture diameter 10 cm; Bit rate 10 Gbit/s

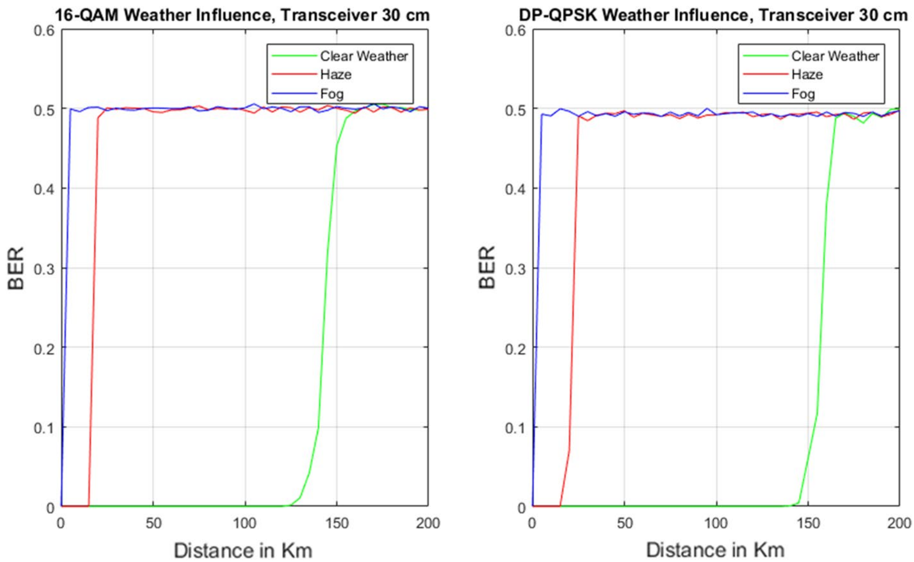


Fig. 7 BER showing the distance limit for clear weather, haze, and fog versus distance; Transceiver aperture diameter 30 cm; Bit rate 10 Gbit/s

that both techniques are almost identical. For low attenuation 0.4 dB/km the propagation is possible and the BER is acceptable till approximately 150 km. After exceeding the 150 km range the reconstruction of the transmitted signal in the receiver side is no more feasible, since the BER is too high. For higher attenuation coefficients (4 dB/km, 21 dB/km) in bad weather circumstances, the transmission is achievable between 2–20 km but not above this range.

4.6 1 m Transceiver

Figure 8 shows the BER versus distance in different weather conditions with a 1 m antenna size of both transmitter and receiver. Referring to the figure above, it is notable that both systems are almost identical. For low attenuation 0.4 dB/km the propagation is possible and the BER is acceptable up to approximately 180 km. After exceeding this range, the reconstruction of the transmitted signal in the receiver side is no more feasible, BER is too large. For higher attenuation coefficients (4 dB/km, 21 dB/km) in bad weather circumstances, the transmission is achievable between 2–25 km but not beyond this range.

5 Constellation Diagrams

The simulation results have shown that the signal quality is good until a certain distance and then the link suddenly fails. To investigate this further, constellation diagrams for DP-QPSK and 16-QAM are observed at different bitrates and distances at clear sky with an attenuation of 0.4 dB/km.

5.1 DP-QPSK

The constellation diagrams in Figs. 9 and 10 lead to a different impression. The dots are getting larger depending on the increasing distance, and some bit errors occur already at

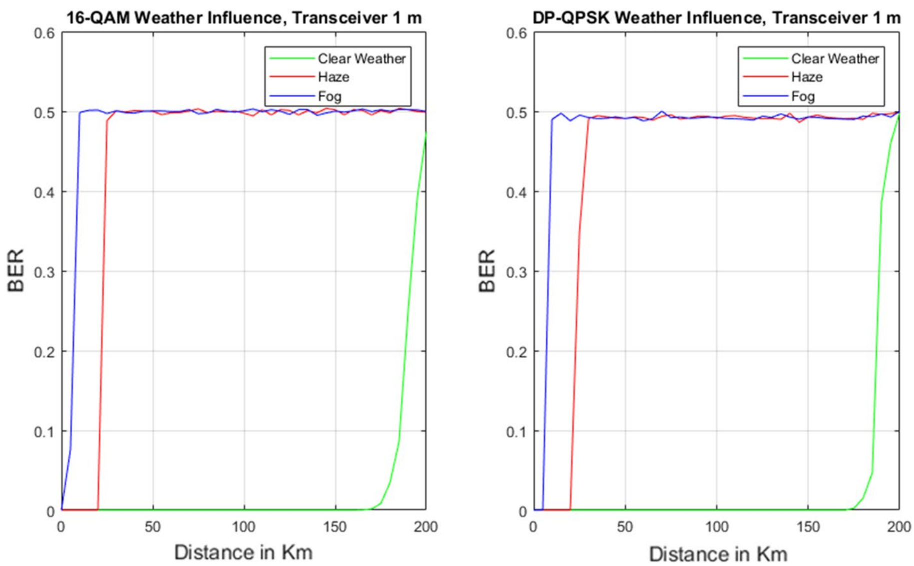


Fig. 8 BER showing the distance limit for clear weather, haze, and fog versus distance; transceiver aperture diameter 1 m; Bit rate 10 Gbit/s

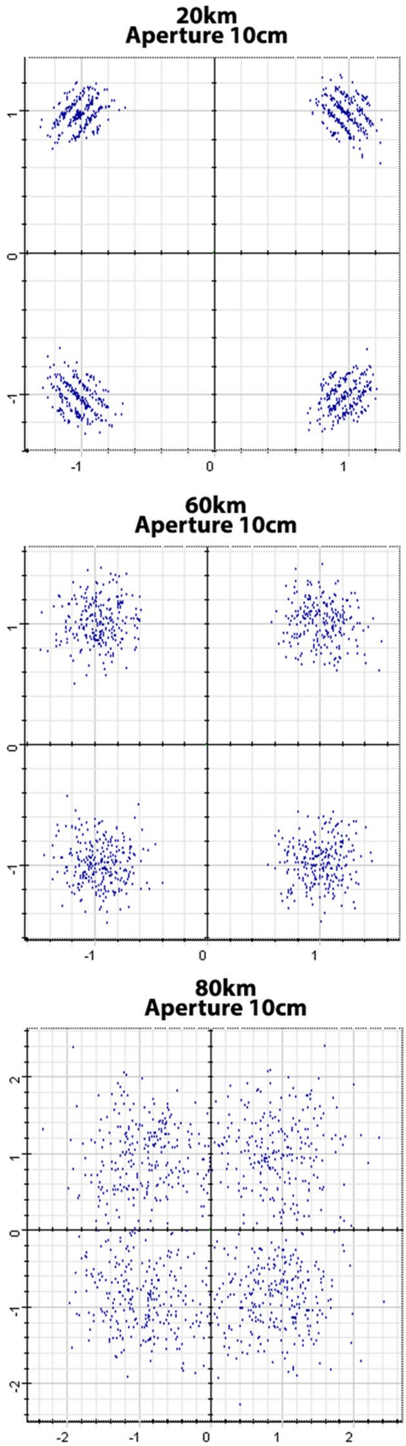
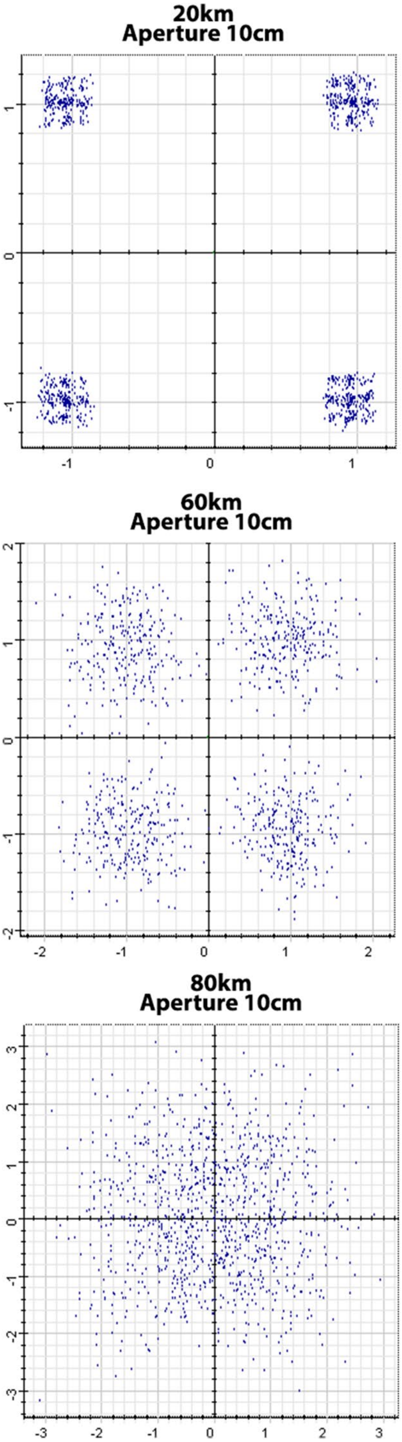


Fig. 9 Constellation diagrams DP-QPSK with 10 Gbit/s. Transceiver diameter 10 cm. Distance 20 km (top), 60 km (middle), and 80 km (bottom). Note: different scales

Fig. 10 Constellation diagrams DP-QPSK with 100 Gbit/s. Transceiver diameter 10 cm. Distance 20 km (top), 60 km (middle), and 80 km (bottom). *Note*: different scales



earlier distances, these are too small to be seen in the figures. At this point the transmitted signal quality is still good enough to demodulate the message. It is also shown clearly that a lower bitrate leads to a higher transmission distance. To have an equal comparison, the signal power of the DP-QPSK is doubled to 33 dBm instead of 30 dBm, this is necessary because the constellation diagram shows only one polarization that represents half of the transmitted power.

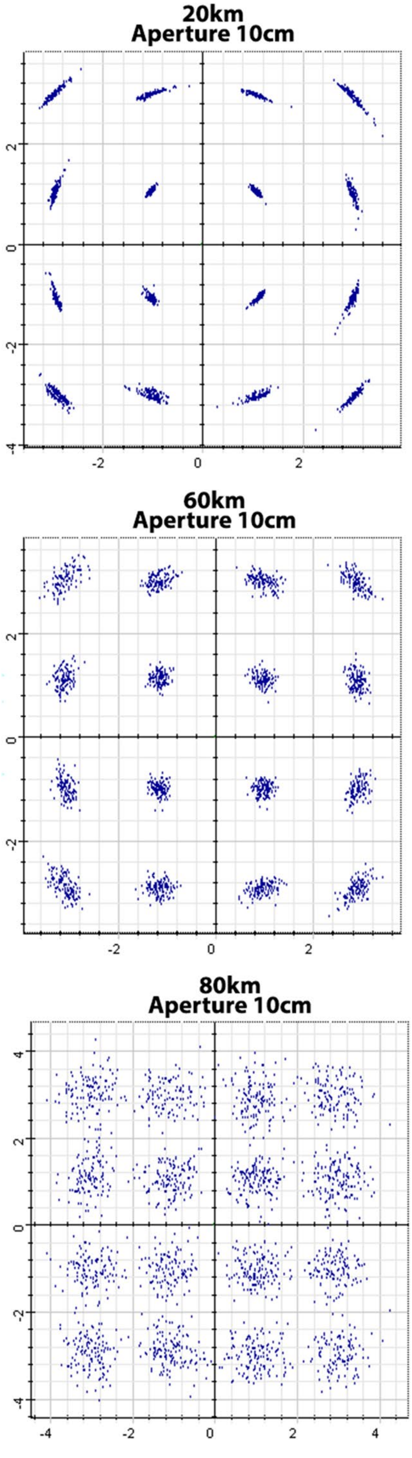
5.2 16-QAM

The same results can be reproduced for the 16-QAM modulation scheme (Figs. 11, 12). It is very interesting that at a low transmission distance of 20 km, a lower bitrate leads to a higher phase noise. At a larger distance, the signal quality for the low bitrate signal turns out to be better though.

6 Conclusions

The free space optical communications (FSOC) performances have been investigated with the simulation system OptiSystem considering the atmospheric channel, distance-dependent beam divergence, influence of the weather conditions, turbulence, and scattering. Interesting results with different design parameters like distances between the transmitter and receiver, modulation schemes applied, aperture diameters of the transceivers, the influence of fog were achieved and discussed. Even though in the diagrams of the simulation the distance limits with the corresponding BER are shown for each modulation scheme, the transmission distance for the realistic transmission should be chosen far enough from or significantly smaller than these distance limits, in order to achieve the BER of 10^{-6}–10^{-9} in combination with channel coding and forward error correction. While one of the most significant attenuation factors, the beam divergence, is estimated precisely, the results show a significant influence of non-influenceable factors. If a redundant connection at a constant bit-rate is required, the influence of atmospheric changes limits the possible distances significantly, especially the occurrence of fog requires additional planning fade margin. Besides the limitations of a single channel, the bitrates 10 Gbit/s and 100 Gbit/s can be increased by a certain factor, if coarse wavelength division multiplex (CWDM) or even dense wavelength division multiplex (DWDM), which are now standard in the fiber optical communication systems, can be utilized, so that Tbit/s could be possible.

Fig. 11 Constellation diagrams 16-QAM with 10 Gbit/s. Transceiver diameter 10 cm. Distance 20 km (top), 60 km (middle), and 80 km (bottom). Note: different scales



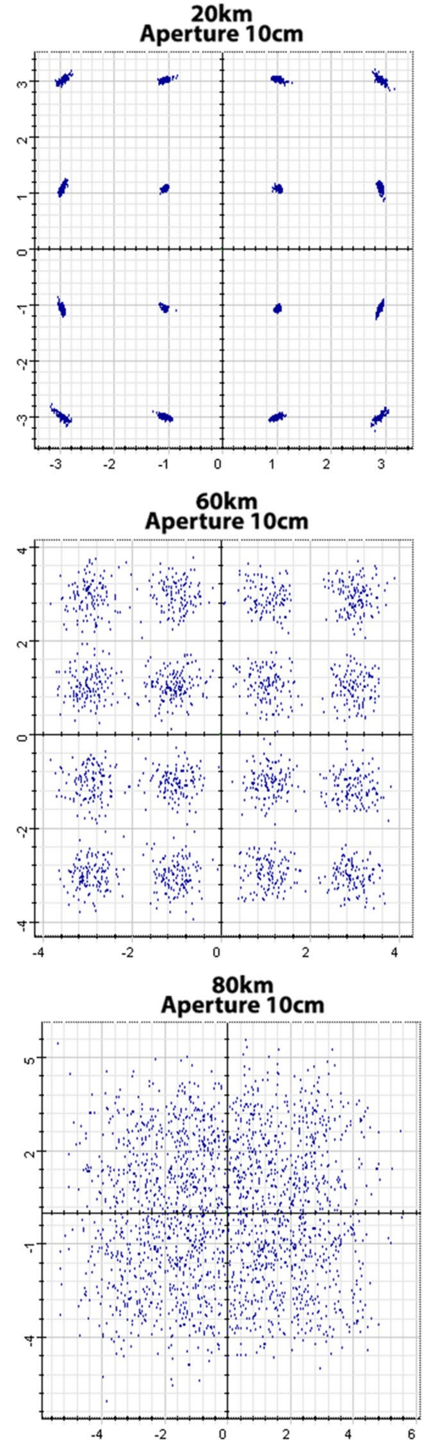


Fig. 12 Constellation diagrams 16-QAM with 100 Gbit/s. Transceiver diameter 10 cm. Distance 20 km (top), 60 km (middle), and 80 km (bottom). Note: different scales

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References

1. Uysal, M., Capsoni, C., Ghassemlooy, Z., Boucouvalas, A., & Udvary, E. (2016). *Optical wireless communications: an emerging technology*. Berlin: Springer.
2. Khalighi, M. A., & Uysal, M. (2014). Survey on free space optical communication: A communication theory perspective. *IEEE Communications Surveys & Tutorials*, *16*(4), 2231–2258.
3. Malik, A., & Singh, P. (2015). Free space optics: Current applications and future challenges. *International Journal of Optics*, *2015*, 7.
4. Lopez-Martinez, F. J., Gomez, G. & Garrido-Balsells, J. M.(2015). Physical-layer security in free-space optical communications. *IEEE Photonics Journal* 7.2 (2015): 1–14.
5. Kaushal, H., Jain, V. K., & Kar, S. (2017). *Free space optical communication* (vol. 1). Gurgaon, Haryana: Springer.
6. Seeber, F. (2007). Light sources and laser safety. *Fundamentals of photonics* 1.2.
7. Jia, Z., Zhu, Q., & Ao, F. (2006) Atmospheric attenuation analysis in the fso link. In *2006 international conference on communication technology* (pp. 1–4).
8. Degnan, J. J. & Klein B. J. (1973). Transmitter and receiver antenna gain analysis for laser radar and communication systems. Tech. Rep. X-524-73-185, NASA GSFC.
9. Kim, I. I., Korevaar, E. J. & McArthur, B.(2001). Comparison of laser beam propagation at 785 nm and 1550 nm in fog and haze for optical wireless communications. In *Proc.SPIE* (Vol. 4214, p. 2637).
10. Shah, S., Mughal, S., & Memon, S. (2015). Theoretical and empirical based extinction coefficients for fog attenuation in terms of visibility at 850 nm. In *2015 International Conference on Emerging Technologies (ICET)* (pp. 1–4).
11. Grabner, M., & Kvicera, V. (2011). The wavelength dependent model of extinction in fog and haze for free space optical communication. *Optics Express*, *19*, 3379–3386.
12. Ali, R. N., et al. (2017). Experimental study of clear atmospheric turbulence effects on laser beam spreading in free space. *International Journal of Applied Engineering Research*, *12*(24), 14789–14796.
13. Optiwave Systems Inc. (2018) Optisystem, user guide and reference manual. Optiwave Systems Inc., Ontario .

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