Investigations on OFDM-FSO transmission system for UAV-to-Ground Links

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Abstract

The seamless deployment of 5G and beyond future wireless networks requires ultra-high information rate, cost-efficient, easily deployable and scalable, front-haul and backhaul framework. Motivated by the growing interest in the application of unmanned aerial vehicles (UAV) to boost conventional cellular mobile networks' coverage and performance, this article proposes a UAV-to-ground terminal communication link based on free-space optics (FSO) technology for front-haul and backhaul network traffic. To enhance the system's traffic carrying capacity, robustness, and spectral efficiency, we propose the integration of orthogonal-frequency division multiplexing (OFDM) in the proposed framework. 20 Gbps 4-ary quadrature amplitude modulated (4-QAM) data signal is transmitted over varying channel conditions. The proposed framework performance is investigated for increasing the range of transmission and divergence angle of the beam. The simulations demonstrate that the proposed 4-QAM-OFDM-FSO framework can provide high information transmission rate for front-haul and backhaul traffic and can be a viable solution for the emerging needs of 5G wireless networks.

1. Introduction

Small-cell deployment at a high density is one of the most critical technologies for providing massive bandwidth and high data transfer rates in future wireless communication networks. [1]. Although the concept of small-cell deployment has been extensively researched over the past few years for 4G LTE architecture, its practical deployment has been challenged due to the difficulty and cost of installing small-cell substations in front-haul and backhaul networks. Presently, researchers and communication engineers are focused on the deployment of 5th generation (5G) wireless networks, for which the small-cell concept is a crucial technique. However, efficient front-hauling and backhauling still prove to be a bottleneck.

In this article, we report the architecture for small-cell deployment, using which small-cell substations are connected to the core network employing a vertical front-haul and backhaul network. The key techniques used in the deployment of our proposed architecture are free-space optics (FSO) transmission, unmanned aerial vehicles (UAV), and orthogonal frequency division multiplexing (OFDM). FSO technology utilizes free-space as the propagation medium and optical light beams as the data carriers to transport information in a line-of-sight (LOS) configuration [2]. Unlike conventional radio-frequency (RF) and microwave communications, it has no licensing restrictions, and there is plenty of available spectrum. FSO links have a small footprint and employ power-efficient components and equipment. By utilizing very narrow optical beam signals to transport information, FSO links are secure, and further, they are immune to interference from other electromagnetic waves and RF signals [3]. FSO links can be quickly installed and re-deployed in urban and rural regions and are considered a key technological solution for solving the last-mile access problem. Owing to these merits of FSO links, they find application in many areas, including terrestrial building-to-building, building-to-ship, inter-satellite, deep space, and military services [4, 5]. The integration of orthogonal-frequency division multiplexing with FSO links can provide various benefits, including (a) improving the spectral efficiency, (b) high-speed long-haul data transportation, and (c) robustness to inter-carrier and inter-symbol interference [6–9].

There are two fundamental front-hauling and backhauling technologies, namely wired and wireless transmission networks. The medium of information propagation in wired networks is copper cables and optical fiber. Optical fiber is regarded as the best option in wired networks due to its many merits. However, the deployment of optical fiber for small-cell substations may not be feasible due to high installation costs and right of the way requirements in some areas [10]. A more cost-efficient technique is wireless front-hauling and backhauling, where the network traffic is transported over microwave or FSO links. The microwave-based communication links utilize 6 – 60 GHz spectrum for data transportation [11]. However, these frequency bands have become extremely congested and require huge licensing costs in many countries. LOS point-to-point networks based on FSO links have garnered significant attraction as they do not have licensing requirements and can be quickly deployed. Current front-hauling and backhauling wireless networks rely on RF-based non-LOS point-to-multipoint networks that operate in the sub-6 GHz frequency range, which is densely populated, prone to interference, and expensive. As a result, future 5G networks will require a paradigm shift in front-haul and backhaul networks. Recently, UAVs have garnered significant attention for transporting cellular and internet traffic in remote areas where infrastructure deployment is not feasible due to high costs or rough terrains. A few examples include the Internet.org project launched by Facebook, where Stratosphere-based communications provide Internet services. Other significant deployments are SkyStation, Satellite, Sky-Tower, Skynet HeliNet, and CAPANINA [12]. Different terms are used in literature for UAVs, including unmanned aerial systems (UAS), high-altitude platforms (HAP), and networked flying platforms (NFP) [12]. UAVs include balloons, aircraft-manned and unmanned, and airships present in the lower zone of the stratosphere which vertical height varying from 17 km to 25 km for the sea level [13]. UAVs may need to move/fly in certain cases depending upon climate conditions, network traffic, and coverage requirements. The movement of the UAV can either be controlled by a human operator in the ground station (autonomous operation) or can be independent (non-autonomous operation) [14].

2. Proposed Architecture

Figure 1 illustrates the graphical architecture of the proposed front-hauling and backhauling links for future 5G networks based on a UAV-to-ground station-based FSO transmission system. The proposed architecture can be deployed complementary to terrestrial front-haul and backhaul networks during challenging situations like a terrestrial front-haul and backhaul network failure due to natural disasters or high coverage requirements during a sports event. Further, the proposed architecture can reliably provide information transmission in hard-to-reach regions where optical fiber and microwave links are not feasible. Such regions include rural areas with rough geographical settings such as mountains and highly populated urban areas. The proposed architecture comprises several UAVs, which are connected. The flying height for the UAV may range from a few hundred meters to 25 km (usually 20 km) depending upon the climate conditions and coverage area. All the UAVs can transmit data to each other using FSO transmission. The UAVs are also connected to small-cell substations using point-to-point FSO links. Each small-cell substation has a precise LOS configuration with UAV. In the case of the non-availability of LOS, the small-cell substation can be served by a neighbouring substation, which has a clear LOS with the UAV.

3. Implementation And Channel Modeling

Figure 2 elucidates the proposed UAV-to-ground terminal FSO transmission link using OFDM signals. 20 Gbps binary information is generated using a PRBS and mapped onto 4-QAM symbols using 2-bits/symbol. The 4-QAM signal is directed to the OFDM modulator performing various signal processing, including serial-to-parallel conversion of binary data, inverse fast Fourier transformation (IFFT) algorithm, the addition of cyclic prefix (CP), parallel-to-serial conversion, digital-to-analog conversion, and signal filtering. The OFDM component specifications are 1024-IFFT points, 512-subcarriers, 15 dBm average power, and 32-CP. The OFDM electrical signal is in-phase quadrature modulated at 7.5 GHz frequency and then optically modulated over a laser beam from continuous wave laser using a Mach-Zehnder modulator (MZM). The optical beam bearing information is then transported towards to ground station through the free-space channel. At the ground station, direct detection is used for retrieving data. The PIN-photodetector converts the optical beam to the electrical signal, further demodulated using OFDM and quadrature demodulator sections. Finally, the information is decoded using the 4-QAM sequence decoder.

The free-space channel between the UAV and ground terminal is mainly affected by attenuation offered by external climate and turbulent atmospheric conditions. The path loss h_l^p can be estimated using exponential Beer-Lambert Law [15]:

$$h_l^p = \exp(-\sigma L_p)$$

1

where σ signifies the specific coefficient of attenuation for external climate conditions and L_p is the transmission distance from the UAV and ground station, which is given as:

$$L_p = {}^{H_p}\big/_{\cos\zeta_p} \qquad (2)$$

where H_p signifies the height of the UAV from sea level and ζ_p is the zenith angle which is defined as the angle between UAV and ground station. Atmospheric turbulence h_a^p is a random phenomenon due to random fluctuations in the atmospheric refractive index structure profile due to inhomogeneities in the external pressure and temperature conditions, leading to optical turbulent eddies. These optical eddies vary the phase and intensity of the optical signal at the receiver plane and increase the BER. We have used the Gamma-Gamma turbulence model in the reported work given as [16]:

$$f_{h_a^p} = \frac{2(\alpha\beta)^{\frac{\alpha+\beta}{2}}}{\Gamma(\alpha)\Gamma(\beta)}(h_a^p)^{\left(\frac{\alpha+\beta}{2}\right)-1}K_{\alpha-\beta}\left(2\sqrt{\alpha\beta h_a^p}\right)$$

3

where $K_{\alpha-\beta}(.)$ signifies the modified-Bessel function having $(\alpha-\beta)$ order, Γ signifies the Gamma function, $\alpha,$ and β signify the number of large-scale and small-scale eddies given as [17]:

$$\alpha = \left\{ \exp\left[\frac{0.49\sigma_R^2}{\left(1 + 1.11\sigma_R^{12/5}\right)^{\frac{7}{6}}} \right] - 1 \right\}^{-1}$$

4

$$\beta = \left\{ \exp\left[\frac{0.51\sigma_R^2}{\left(1 + 0.69\sigma_R^{12/5}\right)^{\frac{5}{6}}} \right] - 1 \right\}^{-1}$$

5

where σ_R^2 signifies the Roytov variance and is expressed as [18]:

$$\sigma_R^2 = 2.25k^{\frac{7}{6}} sec^{\frac{11}{6}}\left(\zeta_p\right) \int_{h_0}^{H_p} C_n^2(h)\,(h - h_0)^{5/6} dh$$

6

where k signifies the wavenumber, h_0 represents the height of the ground terminal, C_n^2 signifies the refractive index structure parameter, which can be expressed using the Hufnagel-Valley model as [19]:

$$C_n^2(h) = 0.00594\left(\frac{\omega}{27}\right)^2 \left(10^{-5}h\right)^{10} \exp\left(\frac{-h}{1000}\right) + 2.7 \times 10^{-16} \exp\left(\frac{-h}{1500}\right) + C_n^2(0) \exp\left(\frac{-h}{100}\right)$$

7

where ω signifies RMS value of air velocity, h signifies the height from the sea level, $C_n^2(0)$ is the ground value of C_n^2 which is $1.7 \times 10^{-14} m^{-2/3}$.

4. Results

The proposed systems' transmission performance is investigated for increasing range, power, receiver diameter, and attenuation. The system and link parameters while performing simulations have been taken from [14, 20]. Fig. 3 elucidates the transmission performance of the proposed system with increasing transmission range in terms of BER for different laser input power levels. For 15 dBm laser power, log(BER) is -2.22, -1.16, and -0.65 and for 20 dBm laser power, log(BER) is -4.21, -2.32, and -1.24 at range of 18, 21.5, and 25 km respectively. Results show that increasing range increases BER of the signal due to increasing attenuation and turbulence losses. Further, as the laser power increases, BER improves. Fig. 4 elucidates the constellation plots at 20 km for different laser power levels.

Figure 5 elucidates the transmission performance of the proposed system with increasing attenuation for different laser input power levels. For 15 dBm laser power, log(BER) is -2.60, -1.01, and -0.47 and for 20 dBm laser power, log(BER) is -4.21, -2.03, -0.79 under 0.8, 1.15, and 1.5 dB/km atmospheric attenuation coefficient respectively. It can be observed that as the attenuation coefficient increases, BER also increases. Fig. 6 elucidates the constellation plots under 1 dB/km attenuation coefficient for different laser power levels.

Figure 7 elucidates the transmission performance of the proposed system with increasing angle of beam divergence for different receiver antenna aperture diameter. For 10 cm aperture diameter, log(BER) is -2.01, -0.59, and -0.41 and for 20 cm aperture diameter, log(BER) -4.21, -1.24, and -0.70 under 0.4, 1.2, and 2 mrad divergence angle respectively. It can be observed that as the divergence angle increases, BER also increases. Fig. 8 elucidates the constellation plots under 0.8 mrad divergence angle for receiver aperture diameter.

5. Conclusions

We proposed a framework for 4-QAM-OFDM-FSO transmission for vertical front-haul and backhaul networks from UAVs to Ground stations for deployment in high-speed 5G wireless transmission links. 20 Gbps OFDM signal is transported from UAV to ground terminal, and the link performance is evaluated for increasing range, beam divergence, input laser power, and receiver aperture diameter. The results demonstrate that 20 Gbps information is transmitted favorably across a range of 18 – 25 km. The proposed architecture can be deployed for future high-speed front-haul and backhaul network traffic transmission.

Declarations

Funding: No funding was received for this work.

Availability of data and materials: No data sets were generated or analyzed in the present study.

Code availability: Present work was done using Optisystem tool.

Conflict of interest: The authors declare that they have no conflict of interest.

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Figures

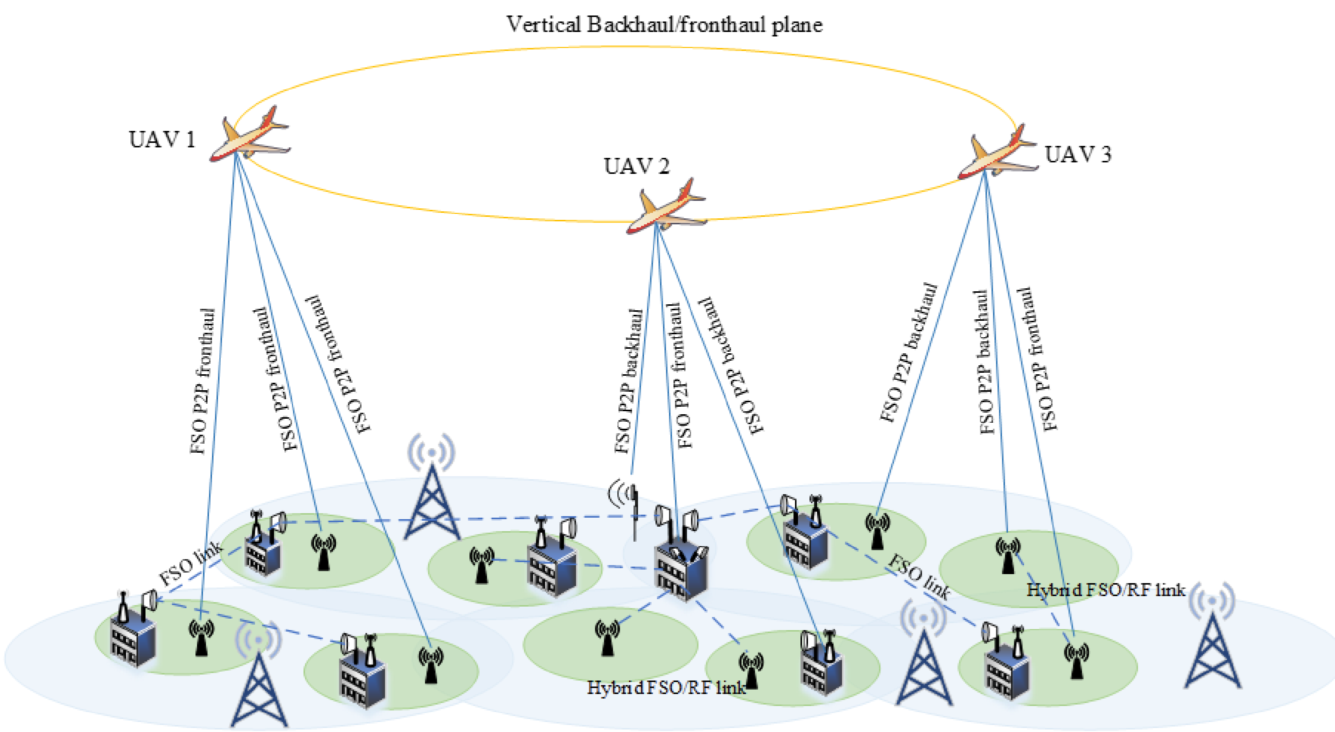

Figure 1

Proposed architecture of vertical front-haul and backhaul network based on FSO transmission

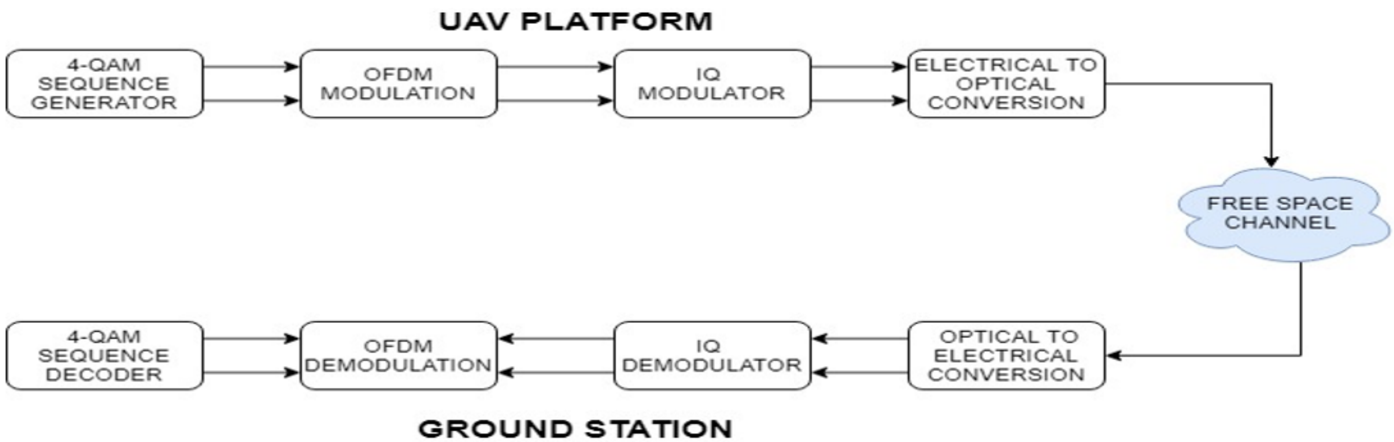

Figure 2

Implementation of UAV-to-Ground links using OFDM-FSO transmission

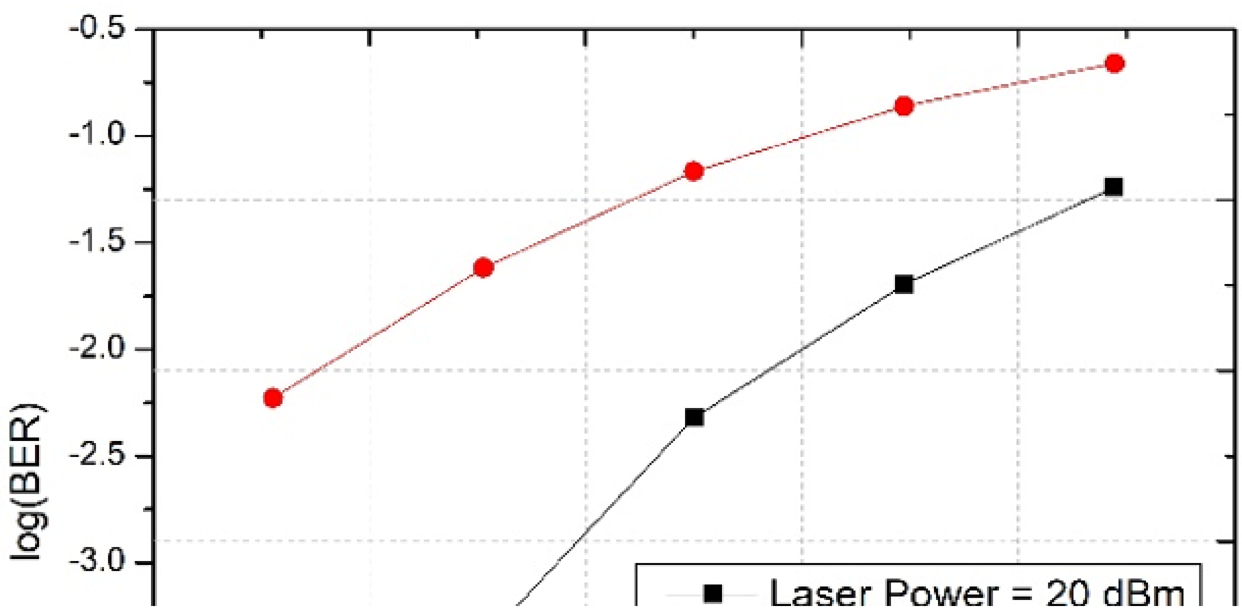

Figure 3

log(BER) investigation for increasing range and input power

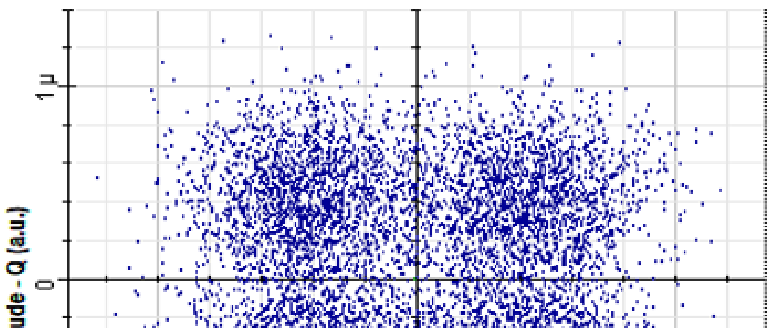

Figure 4

Constellation plots for (a) 15 dBm (b) 20 dBm laser power at 25 km

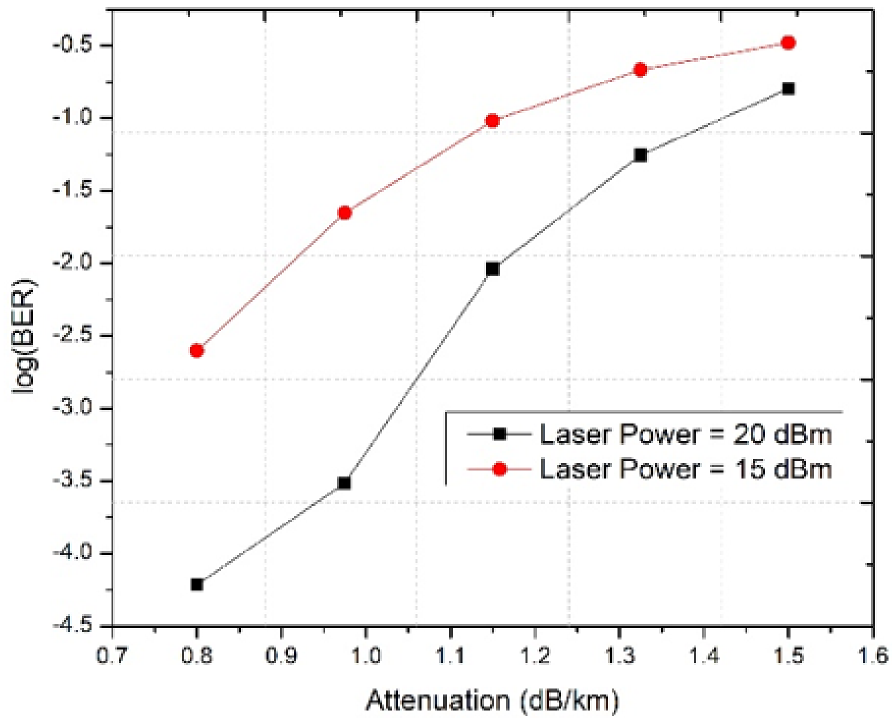

Figure 5

log(BER) investigation for increasing attenuation coefficient and input power

Figure 6

Constellation plots for (a) 15 dBm (b) 20 dBm laser power under 1 dB/km attenuation

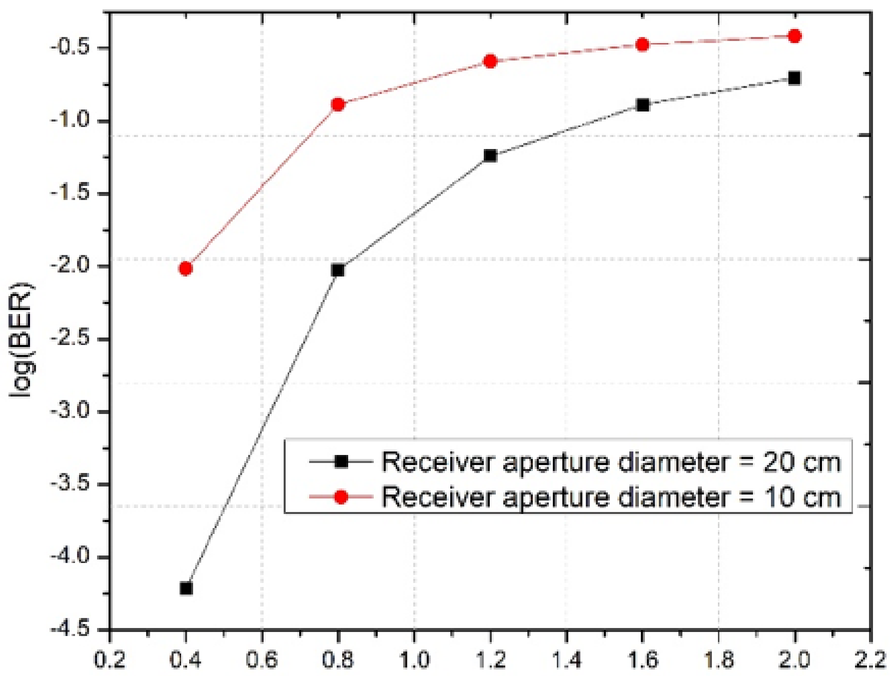

Figure 7

log(BER) investigation for increasing beam divergence angle and receiver aperture diameter

Figure 8

Constellation plots for (a) 10 cm (b) 20 cm receiver aperture diameter under 0.8 mrad beam divergence