Performance analysis and optimization of hybrid fiber/FSO dual-polarization 16-QAM data link under different weather conditions

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***Abstract*—The access transport networks are currently facing the traffic congestion problem due to rapid growth of user's needs. The future fifth generation (5G) and beyond networks must overcome this issue to ensure that end-users have access to high-speed networks, especially in the ace of internet of things (IoTs), big data and so on. In particular, free-space optical (FSO) communication is technology that transmit large bandwidth's signal wirelessly by using light propagating in free space and enables to realize this existing problem. In this paper, the access network configuration, i.e. transmitter to hybrid SSMF/FSO channel then to receiver, has been studied. We analyzed and evaluated system performance Q-factor of the dual polarization multiplexed 16 quadrature amplitude modulation (DP-16QAM) signal with hybrid configuration of SSMF and FSO links under atmospheric conditions such as clear air, rain and heavy weather. The lowest bandwidth of signal DP-16QAM through hybrid 80 km SSMF and 1 km FSO link in heavy weather conditions (25 mm/h) is 40 Gbaud. At the same time, the transmission distance of SSMF, FSO range, beam divergence, and receiver aperture diameter is optimized.**

***Index Terms*—DP 16-QAM, hybrid fiber and FSO, dispersion compensation (DC), weather conditions.**

I. INTRODUCTION

In recent years, the growth in both the scale and quality of telecommunication services such as high-definition TV (HDTV), video-on-demand, cloud computing and high-speed internet access, has been accelerated enormously. Increasing bandwidth in metro area networks (MANs) and access terminal links is in urgent need. Meanwhile, the third and fourth generation networks are currently using a combination of low radio frequency (about a few GHz), fiber optic cables, digital subscriber line (DSL) and coaxial cable, so that the bottleneck issue cannot be avoided. FSO technology can flexibly address links in all network configurations including core networks, MANs, local area networks (LANs) [1]–[6]. High-speed data transmission is guaranteed and authorizing association is secured by using FSO lines in densely populated urban areas, in where fiber optic system is unmanageable to deploy. Many remarkable advantages of FSO system can be described as follows: (i) signal from the transmitting optical FSO telescopes to the receiving one is highly oriented and not disturbed by other radio frequency (RF) systems, (ii) license-free and cost-effective with fast deployment possibility and (iii) inherit and leverage existing network infrastructure and support high-speed data transmission.

Therefore, FSO is a potential candidate that meets the requirements of 5G and beyond mobile network. However, FSO technology also reveals big drawback, i.e. attenuation, due to transmitting signal wirelessly in free space. For example, the attenuation can be up to 300 dB/km in fog conditions. The light transmitted through the heavy rain or in fog environment (known as heavy weather), is absorbed, scattered and reflected quite large, which will limit the reach of FSO link. In addition, the scintillation phenomenon makes the signal amplitude fluctuate, which leads to "image dancing" at the receiver [7], [8]. In [9], a 25 GHz radio over fiber/free space optical (RoF/FSO) system and 10 Gbps 4-QAM/16-QAM/64-QAM modulation formats over 500 m link FSO has been successfully transmitted under the impact of various atmospheric disturbances. In [10], 120 Gbps DP 16-QAM FSO system with the homodyne detector was simulated and analyzed under weather conditions such as rain, fog, haze, and intensity scintillation effect. S. A. Al-Gilani et al. analyzed the performance of a 1 Gbps FSO system with a distance over 1km under rain-loss conditions using the four-bam technique [11]. The influence of different weather conditions on the dense wavelength division multiplexing free-space optical (DWDM/FSO) satellite link 5x16 Gbps was investigated and analyzed in [12]. In [13], the multi-transmitter and multi-receiver FSO system configuration affected by rain, fog, and clear air was proposed, analyzed

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and a 2.5 Gbps FSO system over 2500 km satellite link has been demonstrated in clear air. The parameters of FSO link such as aperture of optical transmitter/receiver telescope and relative intensity noise (RIN) on a high altitude platform (HAP) has been surveyed and analyzed in [14]. In [15], the WDM-FSO system for 2.5 Gbps signal over 150 km was introduced and analyzed under clear weather conditions. A 4 Gbps FSO system around 1.4 km for underground moving train environment was proposed by M. Sivarajani et al in [16]. However, almost research effort on the SSMF/FSO has been focused on modulation format such as QPSK, M-QAM, and parameters of transmitter and receiver optical telescopes have not been evaluated and analyzed.

In this paper, we investigate and optimize parameters of the hybrid SSMF/FSO system under different weather conditions using DP-16QAM modulation format. Furthermore, we evaluate the system performance by optimizing parameters such as SSMF/FSO distances, receiver diameter aperture and beam divergence of transmitter telescope. The simulated results show that the system performance reach $\sim$ 16 dB in clear air and drop to $\sim$ 13 dB in heavy rain for 10 Gbaud DP-16QAM signal. The maximal potential reach of FSO link are $\sim$ 1.7 km with 80 km SSMF for 10 Gbaud DP-16QAM under heavy weather that the performance satisfied the forward error correction (FEC) limit. With optimal values, i.e. 5 mrad of beam divergence and 10 cm receiver aperture diameter, 10 Gbaud DP-16QAM signal is successfully demonstrated through 80 km SSMF/1 km FSO under worst weather conditions.

II. THEORY

For spectral efficiency, the dual polarization modulation technique is performed, in which signals are orthogonal propagated on two planes X and Y. Each plane consists of two parallel Mach-Zehnder Modulator (MZM). The output signals on X- and Y- planes are combined by the polarization beam combiners (PBC) as shown in Fig.1. The continuous wave

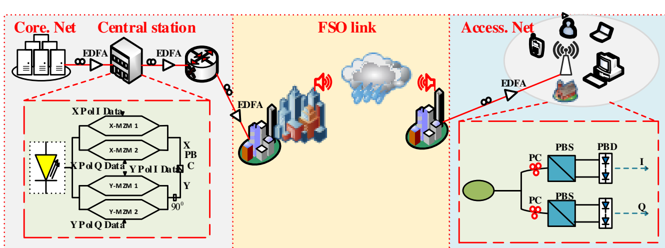

Fig. 1. Hybrid SSMF/FSO transmission system; PBC: polarization beam combiner; OBPF: optical bandpass filter; PC: polarization controller; PBS: polarization beam splitter; BPD: balanced photodiode.

(CW) of lasers at the transmitter with a center frequency $f_s = \frac{\omega_s}{2\pi}$ is described as

$$S(t) = A_S e^{j(\omega_s t + f_s)}.e_S \tag{1}$$

Where, $A_S = \sqrt{P_S}$ is the amplitude of the input signal, $e_S = (e_1 + e_2)e^{j\frac{\pi}{2}}$ is the polarization component, ω_S is the angular frequency. The initial phase is chosen to be zero. The signals on the two branches I (in-phase) and Q (quadrature) of DP-MZM1 and DP-MZM2 on X- and Y- plane are expressed as [17].

$$\begin{bmatrix} V_{I(DP-MZMx)}(t) \\ V_{Q(DP-MZMx)}(t) \end{bmatrix} = \begin{bmatrix} -V_\pi + \frac{2V_p}{p}\sum_m \left\{\sin^{-1}(I_{xm})\, p(t-kT_S)\right\} \\ -V_\pi + \frac{2V_p}{p}\sum_m \left\{\sin^{-1}(Q_{xm})\, p(t-kT_S)\right\} \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} V_{I(DP-MZMy)}(t) \\ V_{Q(DP-MZMy)}(t) \end{bmatrix} = \begin{bmatrix} -V_\pi + \frac{2V_p}{p}\sum_m \left\{\sin^{-1}(I_{ym})\, p(t-kT_S)\right\} \\ -V_\pi + \frac{2V_p}{p}\sum_m \left\{\sin^{-1}(Q_{xm})\, p(t-kT_S)\right\} \end{bmatrix} \tag{3}$$

Here, m is the symbol interval for the 16QAM signal ($m = 1, 2, 3, 4$), T_S is the symbol period, $p(t)$ is the pulse-shaping function.

Optical signal output on X-plane:

$$\begin{aligned} S_{DP-MZMx} =& \sqrt{P_S} e^{j(\omega_S t + \phi_S)} \left[\sin \pi \frac{V_m}{V_\pi} I_x(t) \right. \\ & \left. + j \sin \pi \frac{V_m}{V_\pi} Q_x(t) \right] \left(e_1 + e_2 e^{j\frac{\pi}{2}} \right) \\ =& \gamma_x m_x \sqrt{P_S} e^{j\omega_S t} I_x(t) + jQ_x(t) \\ & \times \left(e_1 + e_2 e^{j\frac{\pi}{2}} \right) \end{aligned} \tag{4}$$

Optical signal output on Y-plane:

$$\begin{aligned} S_{DP-MZMy} =& \sqrt{P_S} e^{j(\omega_S t + \phi_S)} \left[\sin \pi \frac{V_m}{V_\pi} I_y(t) \right. \\ & \left. + j \sin \pi \frac{V_m}{V_\pi} Q_x(t) \right] \left(e_1 + e_2 e^{j\frac{\pi}{2}} \right) \\ =& \gamma_y m_x \sqrt{P_S} e^{j\omega_S t} I_y(t) + jQ_y(t) \\ & \times \left(e_1 + e_2 e^{j\frac{\pi}{2}} \right) \end{aligned} \tag{5}$$

where, $m_x = m_y = \pi\frac{V_m}{V_p}$ is modulation index, γ_x, γ_y is insertion loss of element LiNbO3 MZM.

The SDP-MZMx, SDP-MZMy signals are passed through the PBC. At the output of the PBCs, the optical signal is given as [18].

$$S_{DP-16QAM} = \vec{E_{TE}}\, S_{DP-MZMx} + \vec{E_{TM}}\, S_{DP-MZMy} \tag{6}$$

Here, $\vec{E_{TE}}$, $\vec{E_{TM}}$ respectively, vector for two polarized modes transverse electric (TE) and transverse magnetic (TM). The $S_{DP-16-QAM}$ signal is then transmitted via optical fiber to FSO link.

The architecture of FSO technology is quite simple, it can work in full-duplex (bi-directional) or semi-duplex mode, and that extended in different types of network configuration such as point to point, point to multi-point, ring, mesh [8]. At the transmitter, the signals are optically modulated by lasers, then it will be sent to the divergent lens and transmitted through the atmosphere by the line of sight (LOS) to condenser lens at the receiver, the power at the receiving telescope is written [19].

$$P_{Rx} = P_{Tx}\frac{d_{Rx}^2}{d_{Tx}+\mathrm{f}R_{FSO}}10^{-a\frac{R_{FSO}}{10}} \quad (7)$$

In which, P_{Tx}, P_{Rx} are the power at the transmitter and receiver respectively. d_{Tx}, d_{Rx} are the aperture diameter of transmitter and receiver antennas respectively. R_{FSO} is the distance between the transmitting and the receiving telescope, α is the signal attenuation loss parameter in the atmosphere, ϕ is beam divergence (mrad). d is beam divergence (mrad). The light radius to receiver lens d is related to transmitting distance $\mathrm{R_{FSO}}$ and described as [8].

$$d = R_{ROF}{}^{*}tan\left(\frac{\phi}{2}\right) \quad (8)$$

According to [1], Beer-Lambert's law expresses the relationship of signal attenuation, the transmission distance between two telescopes of the FSO link and the wavelength transmitted through the atmosphere

$$P_S(\lambda, R_{FSO}) = \frac{P_{Rx}}{P_{Tx}} = exp\left[-\gamma_{\mathrm{t}}(\lambda)\, R_{FSO}\right] \quad (9)$$

In which,$P_S(\lambda,\ R_{FSO})$, $\gamma_{\mathrm{t}}(\lambda)$ are the transmitted power and total attenuation at the wavelength $\lambda(nm)$ in the atmosphere respectively. Optical signal that transmitted through the atmosphere, is affected by environmental factors. These constituents will cause the appearance of absorption, scatter signals in many directions different leads to energy loss. Hence, the performance and quality of the FSO system will be affected. Expressions of absorption and scattering due to rain, dust in the FSO system are by Stokes's law [10]:

$$\alpha_{scat,\,rain} = \pi a^2 NA.Q_{scat,rain}\left(\frac{a}{\lambda}\right) \quad (10)$$

Where, a is the size of rain in the area $(0.001-0.1)cm$, NA is the population density of rain, $Q_{scat,rain}$ is scattering efficiency. On the other hand, many factors such as x-rays of the sun, factories, air conditioners and the greenhouse effect are causing the scintillation phenomena. Therefore, the signal amplitude is regularly fluctuating and causes "image dancing" in the receiver of FSO systems. To reduce this event, the FSO system should be far distant from the energy dissipation systems and the FSO connections should not be too far [8]. Scintillation index is defined as [10].

$$\sigma^2 = \frac{\langle {I_S}^2\rangle - \langle I_S\rangle^2}{\langle I_S\rangle^2} = \frac{\langle {I_S}^2\rangle}{\langle I_S\rangle^2} - 1 \quad (11)$$

where, I_S is the signal intensity. Gamma-Gamma probability distributed function of atmospheric fading channels is modeled and calculated as

$$P(I_S) = \frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\mathrm{B}(\beta)}{I_S}^{(\alpha+\beta)/2-1}B_{\alpha-\beta}(2\sqrt{\alpha\beta I_S}) \quad (12)$$

$\Gamma(...)$ is the Gamma function, $\mathrm{B}_{\alpha-\beta}(...)$ is the modified Bessel function of the second kind of order $\alpha-\beta$, α, β are parameters of the probability density functions (PDF).

$$\alpha = \exp\left[\frac{0.49\sigma_{\mathrm{Roy}}^2}{\left(1+1.11\sigma_{\mathrm{Roy}}^{12/5}\right)^{5/6}}\right]-1 \quad (13)$$

$$\beta = \exp\left[\frac{0.51\sigma_{\mathrm{Roy}}^2}{\left(1+0.69\sigma_{\mathrm{Roy}}^{12/5}\right)^{5/6}}\right]-1 \quad (14)$$

Roytov variance is calculated using a logarithm

$$\sigma_{Roy}^2 = 1.23C_n^2N^{7/6}{R_{FSO}}^{11/6} \quad (15)$$

C_n^2 is the parameter index refraction structure; N is the optical wave number.

III. SYSTEM INSTALLATION

In the hybrid system SSFM/FSO, the high-speed transmission over hybrid SSMF/FSO for DP 16-QAM signal is investigated and evaluate. At the transmitter, a pseudo binary sequence of 2^{17-1} bits is randomly generated. The input data stream will be split into two parallel sequences by passing through serial-to- parallel converter. These two data streams are fed into 16-QAM modulator independently to map 4 bits into one symbol. After 16-QAM modulator, the in-phase and quadrature (I/Q) signals will be optically modulated with a continuous wave (CW) laser of frequency 193.1 THz, a linewidth of 0.1 MHz and CW output power of 10 dBm on each polarized branch. The structure of each X-, Y- planes of DP 16-QAM consists of M-ary pulse generators DP-MZM1, DP-MZM2 that is operating parallel. Bias voltage of the lower arm is -2 V, the higher arm is 2 V. The output optical signal on each DP-MZM arm is passed through polarization beam combiner to form the DP 16-QAM optical signal which is described in (4) and (5). Erbium-doped fiber amplifier-fiber (EDFA) with noise figure (NF) 4 dB and the SSMF are used in the system. The loss, dispersion, dispersion slope and nonlinearity coefficient of the SSMF are $\alpha = 0.2\,dB/Km$, $D = 17\,ps/Km/nm$, $S = 0.075\,ps/Km/nm^2$, $\gamma = 1.2\,W^{-1}Km^{-1}$, respectively.
The transmission channel between the transmitter and receiver of the FSO link is the atmospheric environment, so that it is considered an atmospheric fading channel. Because the atmospheric parameters are varying and refractive index are random, it causes signal distortion at the receiver of the communication system [20]. In this study, we evaluated the system quality through different atmospheric environments with different attenuation according to conditions such as clear air, haze, moderate rain, heavy rain and fog [21]. Here, the signal at wavelength $\lambda = 1550\,nm$ transmitted wirelessly in free space and the coefficients of the refractive structure index $C_{\mathrm{n}}^2 = 5.10^{-15}m^{-2/3}$ are set permanently. Parameters nonlinear peak power, bandwidth, maximum optical path SSMF, FSO range, beam divergence, the aperture diameter of the receiver telescope will be surveyed and analyzed in the simulation

results. The receiver, the signal is detected by the coherent detector and the electrical dispersion compensation (EDC) is applied to compensate chromatic dispersion. Digital signal processors (DSP) uses to restore carrier frequency, restore time. The EVM, BER, and Q-factor values are calculated from the signal constellation at the receiver. Their relationship is expressed as a formula [22].

$$EVM_{sys} = \frac{\frac{1}{K}\sum_{i=1}^{K}\|S_{\mathrm{i}} - S_{0,i}\|^2}{\frac{1}{K}\sum_{i=1}^{K}\|S_{0,i}\|^2} \qquad (16)$$

$$BER_{sys} = \frac{(1-\mathrm{M}_{\mathrm{mod}}{}^{-\frac{1}{2}})}{\frac{1}{2}log_2 M_{mod}} * erfc\left[\sqrt{\frac{\frac{3}{2}}{(M_{mod}-1).EVM_{sys}{}^2.k^2}}\right] \qquad (17)$$

$$Q_{sys} = 20 * log(sqrt(2) * (erfcinv(2 * (BER_{sys})))) \qquad (18)$$

Where, S_i is the normalized nth symbol in the stream of measured symbols, $S_{0,i}$ is the ideal normalized constellation point of the nth symbol, K is the number of unique symbols in the constellation, M_{mod} is the number of points on the signal constellation. k is the coefficient depending on the type of modulation.

IV. Results and Discussion

Within the scope of this paper, we investigate and optimize many principal parameters affecting the efficiency of the convergence access network using hybrid SSMF/FSO model. We investigate nd evaluate performance of the hybrid system under various environmental conditions by calculating error vector magnitude (EVM) and Q-factor parameters based on the constellation signal at the receiver.

A. The impact of transmitted powers and signal bandwidth

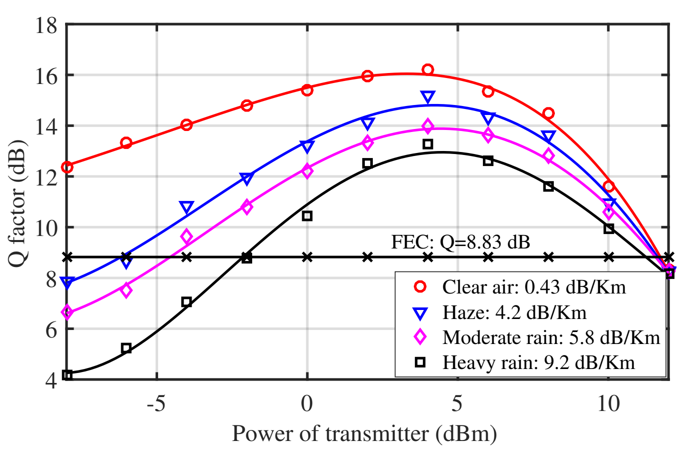

Fig. 2. Q-factor as a function of transmitted power (dBm) of hybrid SSFM/FSO link transmission system for 10 Gbaud DP-16QAM signal under weather conditions.

Fig. 2 depicted the system performance as a function of power of transmitter for 10 Gbaud DP-16QAM over hybrid 80km SSMF/1 km FSO convergence system. The transmitted power is surveyed from -10 dBm to 12 dBm in different weather conditions (i.e. clear air, haze, moderate rain, heavy rain). As a result, in all four simulation scenarios for different weather conditions, the nonlinear peak reaches the threshold at the system power level of 4 dBm. This is called the nonlinear power threshold. When the transmitted power is from -8 dBm to 4 dBm, the system is less affected by nonlinearity phenomena. The system quality increases linearly for all four scenarios. As transmitted power increases over the 4 dBm threshold, the nonlinear effect grows more severely that leads to a decrease of system performance. The surveyed results of the hybrid SSMF/FSO system are indicated that at optimal transmitted power of SSMF and with affection of weather conditions, Q-factors of the system reach $\sim$ 16 dB in clear air, $\sim$ 14 dB in moderate rain and drop to $\sim$ 13 dB in heavy rain for 10 Gbaud DP-16QAM signal.

For any communication system, it is desirable to achieve high speed, high capacity from source to destination but this is not always possible. Because increasing data rate (baud rate) makes the signal pulse-width narrower. Factors such as dispersion and nonlinearity are the cause of inter-symbol interference (ISI). For access network, at the receiver, digital electrical dispersion compensation is applied. However, the compensation method applied at DSP is not efficient for high data rate and high-order modulation. Simulation results in Fig. 3 show that at optimal transmitted power of 4 dBm, the maximal potential signal's bandwidth can be up to 100 Gbaud in clean air and the Q-factor still meets the FEC limit condition. Under bad weather conditions such as haze, moderate rain, heavy rain, the Q-factor value only reaches the FEC limit at bandwidth of 80 Gbaud (640 Gbps), 60 Gbaud (480 Gbps), and 40 Gbaud (320 Gbps), respectively.

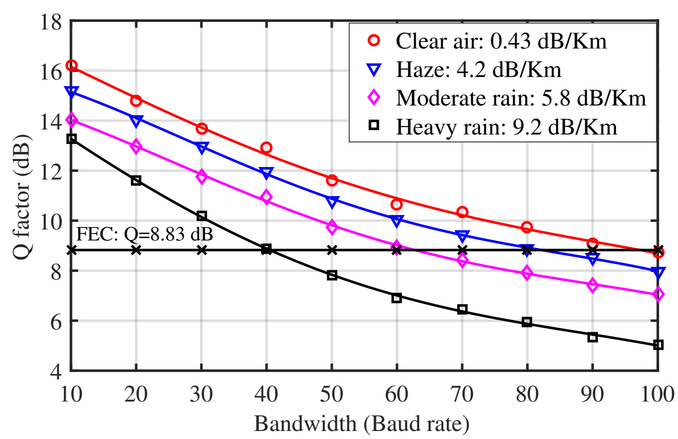

Fig. 3. Q-factor as a function of transmitted bandwidth signal (Gbaud) of a hybrid 80 km SSMF/1 km FSO transmission system for 10 Gbaud DP-16QAM under weather conditions.

B. Performance evaluation of the hybrid SSMF/FSO under different weather conditions

In the section, we investigate the maximal possible reach of SSMF and FSO under different weather conditions with the forward error correction (FEC) limit BER of 3.8e-3. The

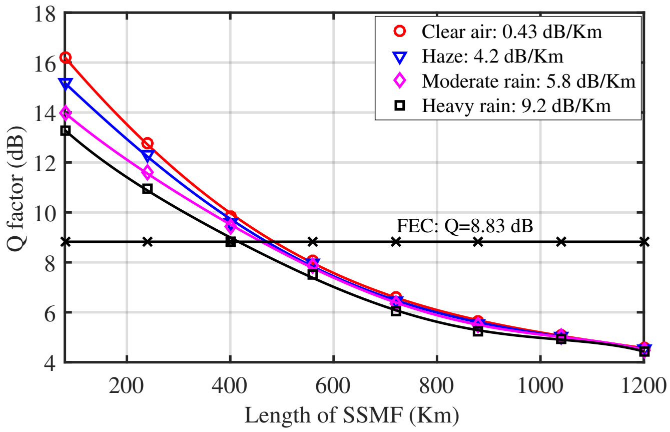

Fig. 4. Q-factor as a function of SSMF length with a fixed distance of 1km FSO for 10 Gbaud DP-16QAM signal under effect of weather conditions

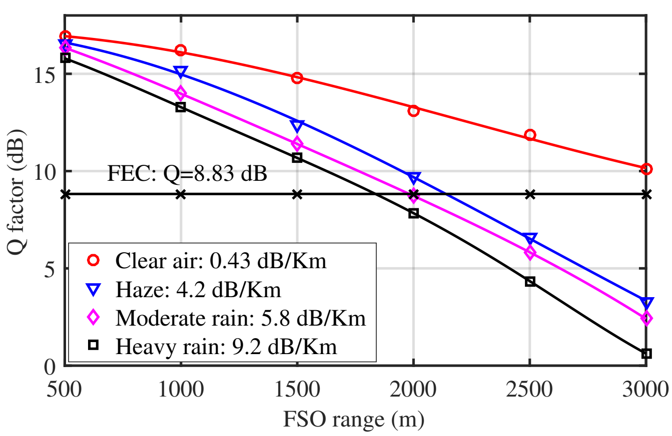

Fig. 5. Q-factor as a function of FSO range with 80 km SSFM for 10 Gbaud DP-16QAM under effect of weather conditions.

parameters of SSMF and FSO link are set as described in section three. At first, the distance of the single mode fiber is investigated from 80 km to 1200 km with a fixed FSO range of 1km. The results in Fig. 4 show that in all four weather scenarios, the distance of fiber optic can reach to 400 km whereas the Q-factor system guarantees the above FEC limit. After 400 km the system decreases linearly. This confirms that as the fiber length increases, the nonlinearity of the SSMF fiber that caused by accumulative optical amplified spontaneous emission (ASE) noise, increase. Therefore, the digital EDC employing at DSP of the receiver does not mitigate the accumulative noise, which causes the system performance under the FEC threshold. On the other hand, the loss due to scattering, absorption in the atmosphere of the FSO connection is also the reason for the performance degradation. The distance of the FSO link channel in free space is also concerned especially for systems using high-order modulation format. Fig 5 shows the results of optimal limitation of FSO range with a fixed 80 km SSMF for 10 Gbaud DP-16QAM signal under different weather conditions. The parameters of the hybrid SSMF/FSO are introduced in section III. The range of FSO link is demonstrated from 500 m to 3.000 m. The simulation results which are depicted in Fig. 5, indicate that in the moderate rain within 2 km of the FSO range, 10 Gbaud DP-16QAM is numerical successfully demonstrated. In clear air condition, the distance of FSO can reach to 3 km and the Q-factor still meets the FEC limit condition.

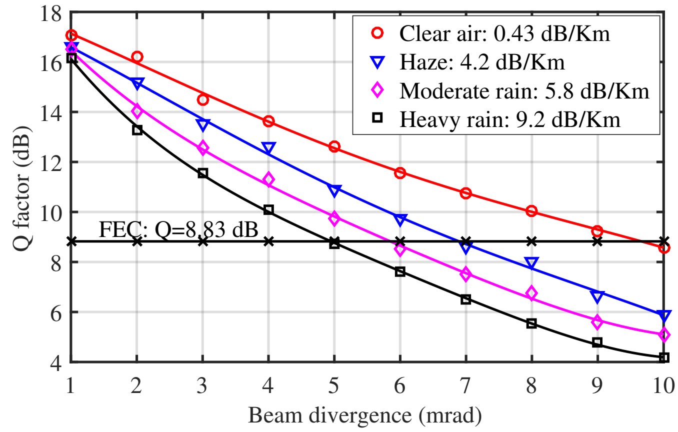

Fig. 6. Q-factor as a function of transmitter beam divergence of the hybrid 80km SSFM/10km FSO transmission system for 10 Gbaud DP-16QAM signal under effect of weather conditions.

C. Optimization of transceiver optical telescope parameters

In this section, we investigate and optimize transceiver parameters such as transmitter beam divergence and receiver aperture diameter that affect the system performance. In the first part, the beam divergence ϕ of the telescope at the transmitter is demonstrated for 10 Gbaud hybrid 80 km SSMF/1km FSO transmission system. As the (8), ϕ is related to FSO range and the beam radius to the receiver telescope (d). As the beam radius increases, under the affection of scattering and atmospheric absorption, attenuation in free space will increase. Therefore, the OSNR of the system reduces. The simulation results are shown in Fig. 6. With weather conditions such as clear air, haze, moderate rain and heavy rain, the optimal beam divergences are $\phi = 10\,\text{mrad}$, $\phi = 7\,\text{mrad}$, $\phi = 6\,\text{mrad}$ and $\phi = 5\,\text{mrad}$, respectively.

Fig.6 shows the system performance Q-factor as a function of receiver aperture diameter (cm) for 10 Gbaud DP-16QAM hybrid transmission system 80 km SSFM/1km FSO. The relationship between receiver power P_{Rx} and receiver aperture diameter d_{Rx} are theoretically calculated as in (7) with the same system parameters that are set in previous section III. The simulation results indicate that in good weather condition, the smallest requirement of receiver aperture diameter is only 4 cm. And when the rain speed is 25 mm/h, the receiver aperture diameter is at least 10 cm. When $d_{Recei} > 10\,cm$ the system Q-factor is ever up the FEC limit. In confirms that in order to achieve the FEC limit under weather conditions, the receiver aperture diameter d_{Rx} should be large. However, in reality, this aperture diameter can not increase arbitrarily depending on specific conditions. RRUs must be small, easy to install,

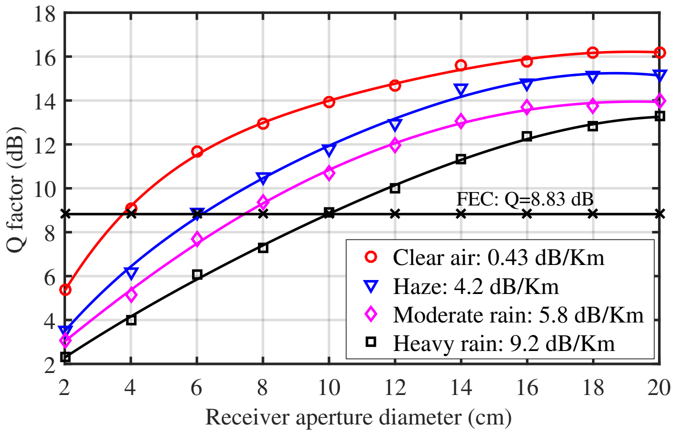

Fig. 7. Q-factor as a function of receiver aperture diameter of hybrid SSFM/FSO transmission for 10 Gbaud DP-16QAM signal under effect of weather conditions

low cost for maintenance and low power consumption which is required for 5G and next generation networks in the future.

V. CONCLUSION

Hybrid SSMF/FSO technology is an advanced technique that can solve congestion problem due to rapid data growth in access network links and is a promising technology for 5G networks and beyond. In this paper, we have analyzed and optimized parameters for DP-16QAM hybrid SSMF/FSO network such as SSMF length, FSO range, bandwidth, characteristics of receiver and transmitter telescope. The simulation results show that in all cases of different atmospheric conditions, the system Q-factor decreases as the baud rate, beam divergence, FSO range increase. The system Q-factor increases as the receiver aperture diameter of the acquisition lens increases. This result will be the basis for further research.

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