Design and Analysis of High-Speed Free Space Optical (FSO) Communication System for Supporting Fifth Generation (5G) Data Services in Diverse Geographical Locations of India

Harjeevan Singh, Nitin Mittal, Rajan Miglani, Harbinder Singh, Gurjot Singh Gaba, and Mustapha Hedabou

***Abstract*—Free space optical (FSO) communication has established a reputation for itself as a next-generation network capable of delivering high-speed data services. In light of the upcoming launch of 5G services, this paper aims to evaluate the performance of the FSO system for the implementation of 5G technology in diverse geographical locations of India. The proposed 16 × 10 Gbps wavelength division multiplexing (WDM) based FSO link uses orthogonal frequency division multiplexing (OFDM) and digital signal processing (DSP) module to mitigate channel-induced limitations. Additionally, the proposed FSO design also employs Erbium-doped fiber amplifier (EDFA) with optimized gain characteristics. Using the data sourced from the Meteorological Department of India, the link analysis reveals that due to weak fog events in coastal areas effective link range of up to 10.75 km can be achieved while maintaining bit error rate of 10^{-9}. Despite dominant foggy conditions in hilly, plains and desert areas, the proposed FSO link significantly limits the degrading effects of channel. Hence, in pursuit of futuristic smart city models, a heterogeneous combination of FSO and 5G infrastructure can conveniently cover diverse geographical locations of India to support high-speed data connectivity.**

***Index Terms*—Free space optical communication, fifth generation networks, meteorological effects, OFDM, WDM, digital signal processing, bit error rate.**

I. Introduction

An ever-increasing number of mobile phone users and exponential rise in the demand for high-speed data services has fuelled the urgent need of exploring alternatives to the existing radio-frequency (RF) infrastructure. The data service providers and researchers across the globe are focusing on smart communication models which can support diverse protocols with seamless integration. Irrespective of different communication verticals being tested currently across the globe, high-speed data rates, wide coverage of mobile networks with reduced latency, and increased spectral efficiency of front-haul and back-haul cellular networks will be some of the common minimal requirements [1]. The evolution of data-hungry applications like massive machine-type communication (mMTC), ultra-reliable low-latency communication (URLLC), and Internet of Things (IoT) for smart cities, etc. have further escalated the need for high-speed communication frameworks [2], [3]. In this scenario, the RF regime and millimeter wave (mmW) links will find themselves insignificant in meeting the demands of futuristic data-hungry devices. Free space optical (FSO) communication is a technique that utilizes free space as an unguided medium for sending the information signal [4], [5]. FSO communication is technologically very closely related to optical fiber links and therefore the former has many transmission characteristics similar to that of the latter. One such feature is the transmission of optically modulated signals which are capable of supporting transmission rates up to the order to Terabits per second ($Tbps$) [6]. Additional features like license-free optical spectrum, plug-and-play installation features, and impeccable signal security, etc. make FSO even more appealing in pursuit of providing cost-effective and high-speed last-mile connectivity [7], [8]. Because RF bandwidth is getting extremely congested while laying optical fiber in urban and remote areas is extremely costly, FSO can be thought of as an interesting option in developing a holistic communication framework for the future.

Concerning the proposed research theme, Fig. 1 illustrates a smart-city ecosystem that uses a combination of RF, optical, microwaves, and IoT infrastructure to serve end-users using different transmission frameworks. The scenario illustrated herein Fig. 1 includes residential areas, medical care/hospitals, agriculture farms, business enclaves, industrial units, and transportation means in the form of road and marine networks. The central office (CO) will be an access point between the communication nodes spread in the city with a high-speed backbone network. The optical transceivers positioned atop of the high-rise buildings will be capable of providing high-speed data access to business houses which can be configured with the CO through

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Fig. 1. 5G enabled smart city network using FSO links.

the closed-loop network topology. The RF transceivers can also be installed to serve as a backup link in case severe downtime affects FSO links. Similarly, with FSO communication, hospitals will be in a much stronger position to serve people living in remote areas. Doctors in the central hospitals can use high-speed FSO links to supervise and prescribe medical procedures for patients in far-flung medical care centers. Moreover, since both visible light communication (VLC) and FSO technically share the same family i.e. optical wireless communication, hence it will be quite convenient to convert FSO signals to VLC and vice versa. Such a mechanism would mean that patient health parameters can be uplinked via VLC and can be further sent to remote doctors through FSO links who can use the same communication link to advise prescriptions. The onset of 5G mobile service is expected to play a major role in further penetration of IoT-enabled services in our daily lives. A major leap in the form of application of IoT devices in agriculture, remote sensing, vehicle-to-vehicle (V2V) communication, and optimization of industrial production, etc. have already been reported [9], [10]. As part of a hybrid network framework, the CO will offer RF connectivity to hundreds and thousands of IoT nodes spread across the city right from agricultural fields to smart household activities.

It will be important here to mention that despite numerous potential benefits, FSO links suffer severe degradation at the hands of unfavorable conditions of the propagation medium i.e. the atmosphere [11]. The meteorological effects such as rain, fog, haze, aerosols, etc. absorb and scatter information-carrying modulated photons thus leading to partial or complete loss of information. For instance, fog which essentially comprises water particles can induce scattering losses to the tune of 350 dB/km, reducing the overall FSO link to less than 50 m [12]. 5G mobile services on the other hand also witness reduced link range, short serviceable area, vulnerability to physical obstructions, and high roll-out costs, hence it is expected that the data access to rural and hostile areas will be a great challenge. The hybrid communication thus depicted in Fig. 1 by the integration of FSO and RF technology can enhance the reliability of next-generation backhaul networks and can facilitate high-speed connectivity to end-users. The markets are now flooded with competent hardware equipment capable of ensuring high-speed free-space optical and radio frequency links. Such a mechanism will help FSO and RF technology to complement one another because none of them is single-headedly capable of serving the connectivity needs of the future [13]. The scope of this work focuses on the analysis and optimization of FSO links for possible integration with 5G networks. For this reason, the impact of atmospheric conditions of different geographical locations of India on the performance of the FSO link has been studied. The rest of the paper is structured as follows: The peer literature considered while formulating the problem statement and its subsequent solution has been presented in Section II while the simulation model designed for investigating the link performance and its mathematical modeling is explained in Section III. Critical discussion on the results obtained from the proposed model has been elaborated in Section IV respectively, while the concluding remarks can be found in Section V.

II. Related Literature

In this section, different research studies carried out globally to evaluate the performance of FSO links based on meteorological data have been elaborated. Mohale *et al.* [14] demonstrated the feasibility of deploying FSO links over various locations in South Africa. For this feasibility study, the meteorological data related to atmospheric visibility and wind speed patterns across different locations over the last four years have been considered. Additionally, the recorded parameters were also used to determine optimal FSO link range under average and worst-case scenarios. In a separate study, Harboe and Souza [15] assessed the possible deployment of FSO links for Brazilian atmospheric conditions. For this analysis, a numerical model to determine the power budget of FSO links while considering various loss factors has been proposed. Using meteorological data collected from various airports across Brazil, the authors here [15] have calculated the link availability and link range for different channel conditions. It was demonstrated that link ranges of 5 km to 8 km can be achieved with 99% link availability in different regions of Brazil. A similar study for Uruguayan weather conditions has been done by Barabino and Rodriguez [16] wherein authors have compared the performance of FSO and mmW links. The optimal link range in the case of FSO link installations in Namibia has been calculated and reported by Handura *et al.* [17]. The authors here have used meteorological data and theoretical models to calculate link margin in the case of average and worst link conditions. More complex evaluation of FSO link performance can be found in [18] where larger channel effects in the form of atmospheric turbulence were also considered. Using visibility data collected from airports from different European countries, Rytov Scintillation theory has been used to determine the atmospheric turbulence and its subsequent effect on FSO link availability. Using Kim's atmospheric visibility attenuation model, Basahel *et al.* [19] ascertained the impact of visibility conditions on FSO links for the tropical climate of Malaysia. Considering different rain rate (mm/min) cases collected from the Malaysian Meteorological Department, authors found that even though FSO links are performance limited due to low visibility conditions, high rain rates, and seasonal forest fires, still, their use as with RF backup is highly recommended for high-speed wireless communications.

A. Problem Statement

If the reports by the reputed international organizations are to be believed, the monthly mobile data traffic, across the globe, will touch 77 $exabytes$ by 2022 [20]. In India by the same time to there will be approximately 781 $million$ smartphone users, 67.2 $million$ 5G users, and 46.2 $billion$ mobile phone application downloads [21]. Consequently, the problem of spectrum congestion will become more dominant shortly. Hence, the early roll-out of 5G mobile services has become more and more critical for handling this enormous data traffic. Although optical fiber-based links are also capably fulfilling this void just like 5G infrastructure, the cost and time involved to deliver last-mile connectivity using either of them will be massive, and developing nations like India will be doomed to be financially unviable. For example, if we take bandwidth to be 1% of the optical carrier frequency ($\approx 10^{16}\ Hz$), the achievable bandwidth will be 100 THz and it is approximately 10^5 times that of RF bandwidth. At the same time, FSO links do not require any purchasing of spectrum license. Along with this, there will be no additional cost of acquiring land and carrying out the installation process as in the case of laying out an optical fiber network [22]. So, in these prevailing conditions, FSO technology can play a crucial role in bridging the gap between the bandwidth scarcity and cost-effectiveness as the FSO optical links are capable of providing huge bandwidth and high data rates at comparatively lower cost in contrast to optical fiber communication.

Earlier, Kshatriya *et al.* [23] investigated the feasibility of FSO links under fog weather conditions for four different cities of India. But the authors have analyzed the visibility conditions only for predicting the link availabilities and the study lacks a suitable FSO system design to estimate the performance of FSO links for practical atmospheric conditions of India. In related research [24], the authors proposed and evaluated the performance of 16 quadrature amplitude modulation (QAM)-orthogonal frequency division multiplexing (OFDM) based FSO systems under fog weather conditions for two different cities of India. The use of spatial diversity of order 8 has also been advocated to improve the link performance under adverse atmospheric conditions. However, it is a well-known fact that the introduction of multiple-input multiple-output (MIMO) configuration for FSO links will significantly add to the increased cost of hardware equipment and link optimization complexity [25]. In addition to this, the proposed setup does not consider any separate compensation mechanism to overcome the adverse effects of channel impairment on the received signal. This can be easily seen from the constellation plots of the received signal which witness unwanted phase shift. The authors in [26] have evaluated the FSO link performance for weather conditions that prevail in southern India. The reported data rate of the proposed system is 1.25 Gbps and it will be insignificant in contrast to the data traffic volume expected in this decade. Additionally, the authors have opted for on-off keying (OOK) modulation which is although easy to implement but suffers from poor spectrum efficiency and vulnerability to adverse effects of atmospheric conditions as the data is encoded directly onto the amplitude of the signal [27]. Similarly, Q-ary pulse amplitude modulation (PAM) along with OOK has also been studied for FSO links. In Q-ary PAM, the instantaneous intensity of the laser is modulated on Q levels and a laser source having a variable intensity of emission is required in such a scenario, which increases the cost factor. Moreover, dynamic thresholding is also required at receiver in case of multilevel PAM [22]. Prabu *et al.* [28] proposed an FSO system with Spectrum Slicing (SS) and Wavelength Division Multiplexing (WDM) for tropical weather conditions of southern India. The proposed design uses 16 channel configuration with each channel capable of supporting data rates of 1.56 Gbps, thus delivering cumulative transmission rates of approximately 25 Gbps. However, we believe that there is a possible scope of improvement in overall data rates which will be in sync with expected data demand shortly to support the implementation of future generation mobile networks and smart city infrastructure in near future.

The possible use of WDM-based FSO links for desert areas has been evaluated in [29]. The proposed system has been investigated for data transmission rates of 0.3 Gbps to 0.7 Gbps with concluding remarks in the favour of a lower data rate FSO link to achieve transmission efficiency. In addition to this, the proposed system in [29] uses a laser source of power 40 dBm, however, such levels of laser power are far beyond human safe limits [30]. The use of complex modulation techniques like differential phase-shift keying (DPSK) for improving the performance reliability of FSO links has been suggested in [31]. Since the information in DSPK modulated signal is stored in phase transitions between two adjacent symbols, this technique suffers from the limitation of the tendency of errors that occur in the form of pairs at the receiver side, resulting in increased error probability as well [32]. In a related study by Siegel and Chen [33], the performance of the proposed FSO link has been investigated under changing atmospheric conditions. The design uses quadrature amplitude modulation (QAM) and quadrature phase-shift keying (QPSK) modulation techniques. These modulation techniques transmit multiple symbols at a time and therefore inter-symbol interference may cause loss of information [34]. In separate research, authors in [11] proposed an FSO link that can achieve link ranges of up to 47 km under adverse channel conditions. However, we believe that authors have considered highly ideal channel conditions as typical terrestrial FSO links range from 300 m to 5 km and may be extended to 8 km to 11 km under clear conditions [35]. Hence, the link ranges of the proposed system design in [11] are not practical link ranges and FSO links of such hypothetical ranges cannot be deployed in practical real-life-based scenarios.

B. Research Motivation and Contributions

In light of the research literature and their shortcomings discussed previously, this section elaborates the motivation and the objectives which have shaped our reported research work. To use FSO as supporting technology in the implementation of 5G, it will be necessary to evaluate how the FSO links behave

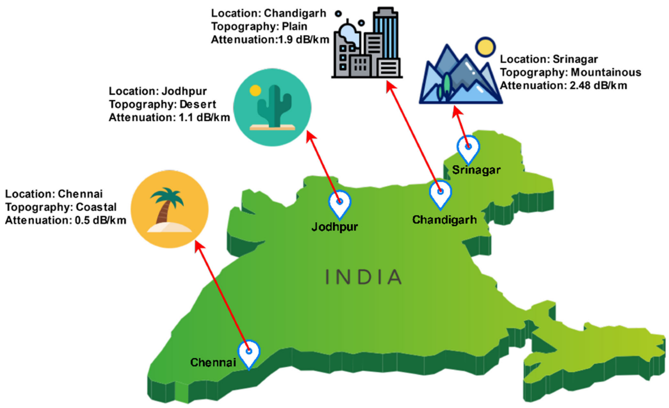


Fig. 2. Different geographical locations of India considered during the FSO link analysis.

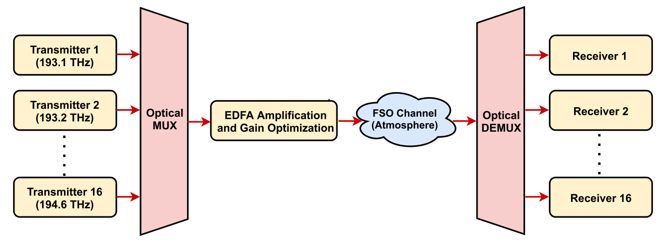


Fig. 3. Block Diagram of proposed 16-Channel WDM based OFDM-FSO system.

across different geographical locations of India. Moreover, all the channel conditions which FSO links will probably face during their operation have been included in this study. For this purpose, the meteorological data have been officially sourced from the Meteorological Department of India. Additionally, the link design parameters have also been benchmarked with notable research works to ensure that all parameters stay within practical limits and are realizable practically using hardware. Meanwhile, Fig. 2 illustrates the diverse locations of India considered in this research study, along with their topographical details and the link attenuation coefficients. These four locations i.e. hilly, plain, desert, and coastal (tropical) reflect the geographical setup of the entire country. Based on these assertions, the research motivation of our proposed work can be summed through following points:

1) To propose a high-speed FSO communication framework for supporting 5G applications across pan India locations,
2) Using actual meteorological conditions of various locations of India and link design parameters to ensure that reported research and proposed link are practically achievable, and
3) To further optimize the performance of the proposed system by using compensation techniques like higher modulation formats, coherent reception, gain optimization and digital signal processing.

The implementation of these objectives has been reported in the subsequent sections of this paper.

III. Proposed System Design

This section elaborates on the link design features and the associated parameters that have been used to investigate the proposed high-speed FSO link. Designed and investigated using OptiSystem™ 13.0, the entire link can be broadly divided into the following subsections:

A. Transmitter Section

As shown in Fig. 3, the transmitter section of our proposed link consists of a 16-channel WDM FSO link (16×10) with a consolidated transmission capacity of 160 Gbps. Since WDM is already very much a matured technology, hence the proposed WDM-FSO link will find easy integration with the existing backbone optical networks. Moreover, WDM is a practical way of enhancing link capacity keep in mind the limits of market available electro-optical converters. Additionally, the use of simultaneous 16 channels will ensure that the end-users will have access to high-speed backbone networks without downgrading the data transmission rates as in conventional RF and copper-wired networks. The effectiveness of the multi-beam FSO system using WDM technology to compensate for the adverse impact of haze weather conditions has also been already reported [36]. Experiments have shown that integration of WDM-FSO system with optical fiber network can support and accommodate user data traffic at 10 Gbps for both simultaneous upstream and downstream communication [37]. 16-QAM modulation technique has been used to design the 16 channel WDM-based OFDM-FSO system in this work as it delivers higher transmission rates and better spectral efficiency [30]. Along with 16-QAM modulation, the use of OFDM improves the immunity of the proposed system design against the multipath fading effects, frequency selective fading, and intersymbol interference, resulting in the increased transmission range of FSO links [38]. In addition to this, 16-QAM and OFDM are industry-graded techniques and the systems based on these techniques can be easily integrated with existing RF and optical fiber-based communication networks to further realize hybrid networks [39]. Moreover, the digital signal processing (DSP) module can also be incorporated into the systems based on 16-QAM and OFDM schemes for the enhanced recovery of signal with minimum errors in the presence of noisy channel. The QAM-OFDM modulated 16 optical transmitters of the proposed link operate in the frequency range of 193.1 THz to 194.6 THz (1552.52 nm to 1540.56 nm), which are further multiplexed by multiplexer as depicted in Fig. 3. The multiplexed signal undergoes Erbium-doped fiber amplifier (EDFA) and gain flattening filter (GFF) based amplification stage before transmission over the atmospheric channel. As the different channels of the WDM-based FSO system suffer from the limitation of uneven gain, the gain optimization has been achieved by using EDFA and GFF in order to ensure constant power levels across different channels.

The block diagram schematic depicting the modulation of each of the transmitters is shown in Fig. 4. The user information data at a rate of 10 Gbps undergoes processing by a 16-QAM sequence encoder to generate in-phase (I) and quadrature-phase (Q) M-ary signals with each symbol being 4 bits long. The I and Q components of QAM symbols are then conditioned with

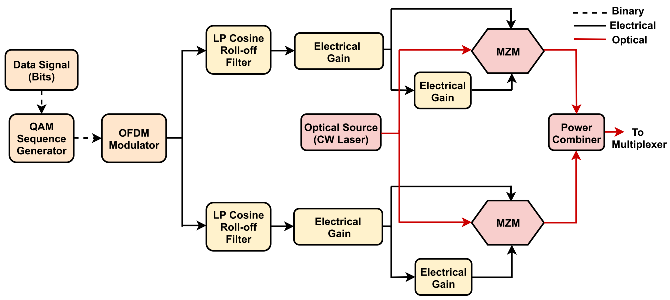


Fig. 4. Transmitter section of proposed 16-Channel WDM based OFDM-FSO system.

512 subcarriers based OFDM modulator to produce a signal which is expected to be more resilient to multi-path fading and inter-symbol interference when it passes through atmospheric channel [38]. The low pass (LP) cosine roll-off filter is used to shape the pulse before transmission for minimizing inter-symbol interference. To up-convert the modulated signal from electrical to optical (E-O) domain, a laser source, and two Mach-Zehnder modulators (MZM) are used. I and Q components of the OFDM modulator are then optically modulated inside MZM by using an external laser source that generates the high frequency optical carrier signal. The outputs of two Mach-Zehnder modulators are combined by using a power combiner and the resulting optical signal is multiplexed with other signals, amplified, and transmitted to the receiver through free space.

B. FSO Channel and Link Attenuation Model

The atmosphere which serves as the propagating medium for FSO signals is largely responsible for attenuation and scattering of information-carrying modulated photons. The presence of heterogeneous particles in the form of aerosols, smog, and meteorological factors like fog, rain, and snow, etc. attenuates the transmitted optical power by the means of absorption and scattering. Out of the various limiting factors known, fog is the most critical attenuating factor. Mathematically, the loss of optical power due to interaction of photons with suspended atmospheric particles can be determined using Beer-Lambert law as [40]:

$$\tau(\lambda, L) = \frac{P_R}{P_T} = e^{-\gamma(\lambda)L} \tag{1}$$

Where $\tau(\lambda, L)$ represents the total transmittance of the atmosphere at wavelength λ, P_t and P_r represents the transmitted and received power respectively, $\gamma(\lambda)$ represents the total attenuation coefficient (per unit length). The total attenuation coefficient can be further written as:

$$\gamma(\lambda) = \alpha_m(\lambda) + \alpha_a(\lambda) + \beta_m(\lambda) + \beta_a(\lambda) \tag{2}$$

Where α_m represents the molecular absorption, α_a is aerosol absorption, β_m is molecular/Rayleigh scattering and β_a is aerosol/Mie scattering. Since the majority of practical FSO systems operate in the wavelength range of 780 nm to 850 nm and 1520 nm to 1600 nm, for which the attenuation resulting from molecular absorption (α_m) and aerosol absorption (α_a) is as low as 0.2 dB/km, hence their contribution to overall attenuation can be neglected [27]. Moreover, the size of molecular constituents present in the atmosphere is also significantly smaller as compared to the wavelengths used for FSO systems, therefore the effect of Rayleigh scattering or molecular scattering (β_m) is also negligible [41]. This leaves us with Mie scattering (β_a) as the only major contributor to the overall link attenuation as the size of aerosol particles, fog, and haze particles is comparable to that of optical wavelengths used for FSO links [27]. The Mie scattering coefficient (β_a) can be calculated by using the theory of Mie scattering as follows [19]:

$$\beta_a = \sum_i n_i Q_i \pi r_i^2 \tag{3}$$

where n_i represents the distribution of i^{th} particle, Q_i represents the scattering efficiency of the i^{th} particle and r_i represents the radius of the i^{th} particle. Since the above-mentioned parameters are very difficult to obtain and the Mie scattering coefficient cannot be calculated easily. Therefore, an empirical formula developed by Kruse [42] is more practical and can be used for calculating the attenuation caused by Mie scattering. The Kruse formula for calculating the Mie scattering coefficient (β_a) is defined as:

$$\beta_a = \frac{3.912}{V}\left(\frac{\lambda}{550(nm)}\right)^{-q} \tag{4}$$

$$q = \begin{cases} 1.6 & V > 50\ km \\ 1.3 & 6\ km < V < 50\ km \\ 0.585\, V^{1/3} & V < 6\ km \end{cases} \tag{5}$$

where λ is the operating wavelength (nm), V is the meteorological visibility (km), q is a parameter that depends on the particle size distribution of scattering particles. However, subsequent investigations by Kim [31] indicated that for dense fog conditions the value of exponent q concerning visibility must be modified to ensure accuracy between mathematical and actual values. Accordingly, (5) has been remodeled as Kim model [31] in the following form:

$$q = \begin{cases} 1.6 & V > 50\ km \\ 1.3 & 6\ km < V < 50\ km \\ 0.16V + 0.34 & 1\ km < V < 6\ km \\ V - 0.5 & 0.5\ km < V < 1\ km \\ 0 & V < 0.5\ km \end{cases} \tag{6}$$

In this study, the diverse geographical locations of India like hilly, plain, coastal, and desert areas have been considered to investigate the variability of performance of FSO links across diverse locations. Srinagar, Chandigarh, Chennai, and Jodhpur represent the hilly, plain, coastal, and desert areas of India respectively. The meteorological data of daily visibilities for all four locations were obtained from the Indian Meteorological Department for five years from 2014 to 2018. As the meteorological data of various locations include a record of visibility conditions on daily basis during the years 2014-2018, the normal

TABLE I
AVERAGE VISIBILITY AND SCATTERING COEFFICIENTS OF VARIOUS GEOGRAPHICAL LOCATIONS IN INDIA

Location	**Average Visibility** (km)	**Scattering Coefficient** (dB/km)
Srinagar (Hilly)	2.9	2.48
Chandigarh (Plain)	3.5	1.9
Jodhpur (Desert)	4.9	1.1
Chennai (Coastal)	9.4	0.5

as well as extreme harsh atmospheric conditions have been considered in this work to investigate the robustness of the proposed system design for diverse geographical locations of India. This meteorological data was used to calculate the average visibilities for all locations. Chennai has recorded maximum average visibility of 9.4 km as it is situated on the Coromandel Coast of the Bay of Bengal and experiences lesser fog weather conditions throughout the year. Jodhpur is a desert location in the northwest of India and experiences winter and fog weather conditions from November to February. So, the average visibility of Jodhpur, with a value of 4.9 km, is comparatively lesser than Chennai. Chandigarh is a plain area situated in the north of India and experiences extreme winter weather conditions from mid of November to mid of February, reducing the average visibility to 3.5 km. Srinagar, being the hilly area in the north of India, has recorded minimum average visibility of 2.9 km due to more fog events throughout the year.

The Mie scattering coefficient (in dB/km) for all locations has been calculated by using (4) and (6) and tabulated in Table I. It has been seen that the locations with higher average visibility result in lower Mie scattering coefficients and the locations with lower average visibility give higher values of the Mie scattering coefficient. Consequently, the Mie scattering coefficient is minimum for the coastal areas like Chennai while for hilly areas like Srinagar, it increases to 2.48 dB/kmdB$/$km. The Mie scattering coefficient for Chandigarh and Jodhpur is 1.9 dB/km and 1.1 dB/km respectively. The scattering coefficients have been used to determine FSO link behavior which has been presented in later sections of this paper.

C. Receiver Section

The FSO signal propagating over the atmospheric medium is received in a degraded form from where it is split back to 16 channels as shown in Fig. 3. Each of the receiver sections of our proposed link is capable of retrieving the original modulated information by the means of coherent detection. Fig. 5 represents the different layers of the proposed receiver section which includes coherent detection, OFDM demodulator, and digital signal processing unit. The coherent detection section converts the incoming FSO signal to the electrical domain which then serves as input for the OFDM demodulator. The demodulated signal is fed to the DSP module to compensate for the atmospheric channel losses. At last, the QAM decoder decodes the compensated signal to extract the information signal. In comparison with direct detection, coherent reception boasts of a slew of advantages which include high spectral efficiency and improved receiver sensitivity. The process of coherent detection of optical signals has been explained with help of Fig. 5(b). The incoming optical beam homodynes with a local oscillator (laser source), once as original signal and other time as $\pi/2$ shifted version. Each of the homodyne coupled signals is then converted to electrical format using photodetectors arranged in balanced detection form. The electrical subtraction stage is essentially responsible for the cancellation of common-mode and background noise which is significantly responsible for loss of information in FSO signals. The electrical signal so obtained is then demodulated for its OFDM components followed by DSP module conditioning.

The DSP module, shown in Fig. 5(c), repairs the received signal for any errors related to timing, phase, and/or frequency. The I and Q components of the transmitted signal obtained after OFDM demodulation pass through 3^{rd} order Bessel filter which preserves the signal wave shape to ensure proper recovery of the information. The second stage of the DSP module is that of the cubic interpolation-based signal re-sampling done to improve the signal resolution and to mitigate the degrading effects of noise. I and Q components of the modulated signal should ideally remain orthogonal to each other, however, atmospheric scattering may cause orthogonality imperfections [46]. Quadrature Imbalance (QI) compensation stage is used to minimize the amplitude and phase imbalances between the I and Q components of the received signal. The adaptive equalizer has been incorporated to suppress the intersymbol interference and timing errors [47]. Any probable mismatch between the transmitted optical signal and the signal of the local oscillator frequency will cause a relative angular shift in the characteristics of the received signal thus leading to inter-carrier interference. Hence, frequency offset estimation (FOE) is employed to remove the frequency offset in the received signal while the carrier phase estimation (CPE), which uses the blind phase search (BPS) algorithm, is responsible for compensating the degrading effects of phase noise due to laser sources [48]. The design parameters which have been used to investigate the proposed link have been tabulated in Table II. The listed parameters in Table II have been sourced and benchmarked with reputed peer literature to ensure implementation variability of the proposed link [22], [43]–[45].

IV. RESULTS AND DISCUSSIONS

The transmitter and receiver sections shown in Fig. 4 and Fig. 5 respectively have been tested for link parameters listed in Table I and Table II to ascertain link performance patterns which have been discussed in this section. Since we have proposed the use of WDM-FSO links as a measure to enhance link capacity, however, it must be noted that WDM-based FSO links are highly vulnerable to inter-channel crosstalk which is caused by atmospheric scintillations and amplifier attenuation emission (ASE) noise due to optical amplification stage. In case of occurrence of either of these events, the bit error rate at the receiver increases thus leading to loss of information, therefore,

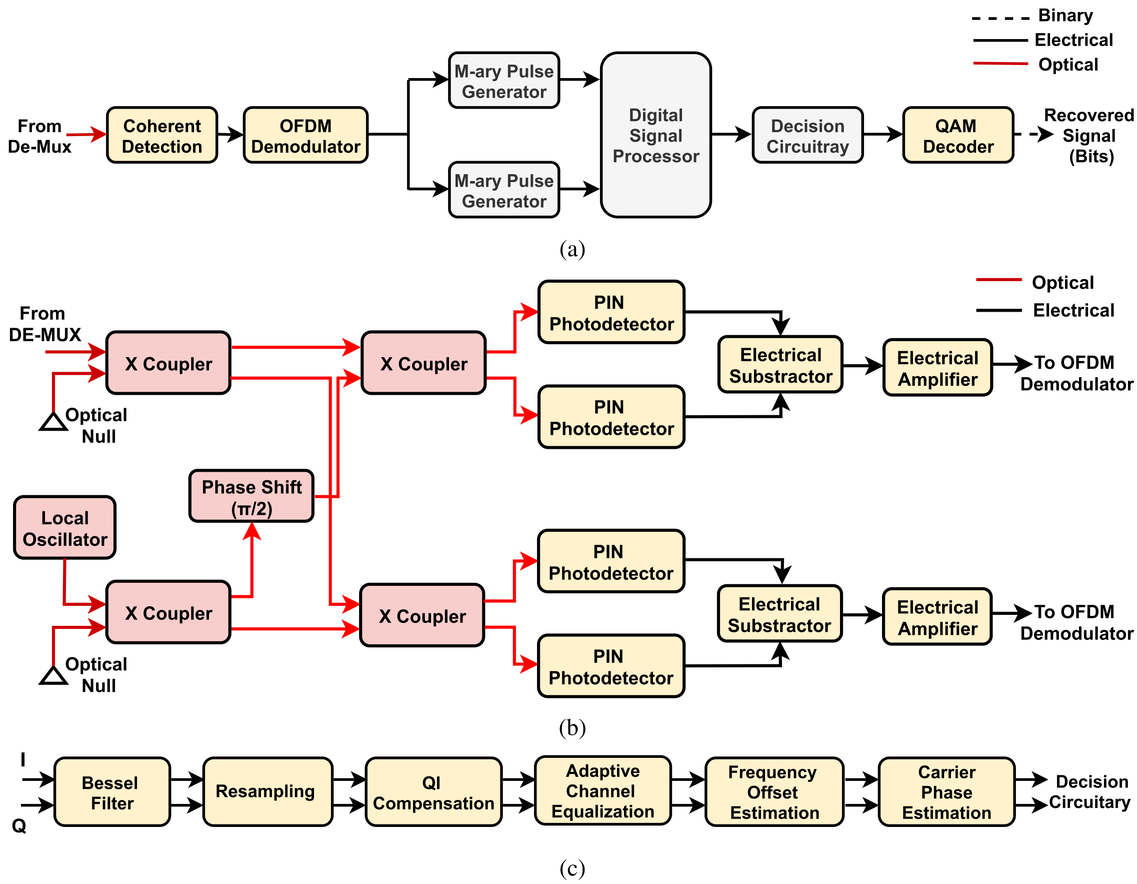


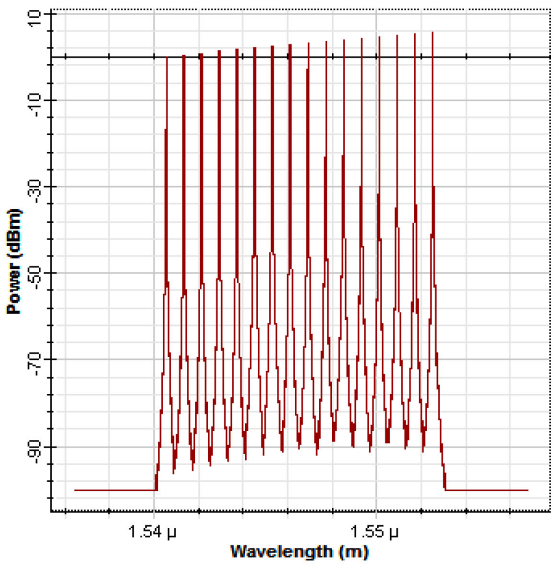
Fig. 5. (a) Receiver section of proposed 16-Channel WDM based OFDM-FSO system (b) Coherent Detection module of receiver (c) DSP module of receiver.

TABLE II
SIMULATION PARAMETERS [22], [43]–[45]

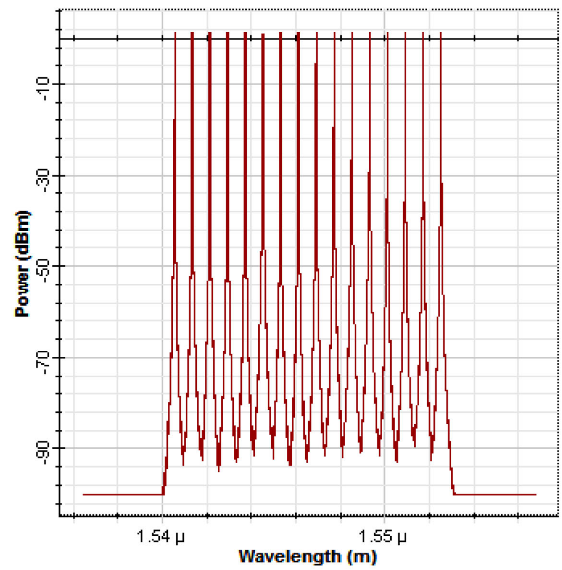
Link Parameter	**Value**
Modulation scheme	$16{-}QAM$
Transmission rate of each channel	10 $Gbps$
Power of laser source	10 dBm
Number of channels	16
Spacing between channels	100 GHz
Laser frequency	193.1 THz to 194.6 THz
Pump characteristics (EDFA)	Forward/100 mW/980 nm
Amplifier gain (EDFA)	12 dB
Amplifier length (EDFA)	5 m
Aperture diameter of transmitter	5 cm
Aperture diameter of receiver	20 cm
Beam divergence angle	2.5 $mrad$
Number of FFT Points	1024
No. of subcarriers	512
Prefix points	64
Sequence Length	65536 $bits$
Photodetector Responsivity	1 A/W
Dark current	10 nA

to minimize these effects, the use of tight filtering at the receiver end and gain optimized amplification at the transmitter has been incorporated. Gain optimization helps in achieving flat gain across all WDM channels thus minimizing signal-to-noise ratio (SNR) discrepancy across the channels and easing the process of signal re-configuration (signal add/drop) which is critically required when integrating with backbone networks.

The spectrum of the proposed FSO system design at various stages of the amplification process has been depicted in Fig. 6 with Fig. 6(a) illustrating the optical spectrum of the FSO signal after the amplification stage using EDFA only. It has been observed that the gain of EDFA is not constant for all wavelengths of the proposed link and consequently, the power levels across various channels vary from 0 dBm to 5.5 dBm. To achieve the flatness in the gain of the EDFA amplifier, GFF has been employed in the proposed link. As a result, the gain flatness has been achieved for the proposed 16-channel FSO link and the power levels across all channels have been stabilized around 1.1 dBm as illustrated in Fig. 6(b). Fig. 7 depicts the comparison of the optical power of various wavelengths across different channels in the case of EDFA amplification only with the power levels achieved after gain optimized EDFA amplification. After achieving the gain flatness for the proposed FSO system design, we have analyzed the behavior of link attenuation (dB) with different link ranges of the proposed FSO system design for various geographical locations of India considered here. As per the obtained analysis shown in Fig. 8(a), it is evident that although the total attenuation increases with the link range but the quantum of increment is location dependent. For example,



(a)



(b)

Fig. 6. Spectrum of proposed 16-Channel WDM based OFDM-FSO system after (a) amplification using EDFA only (b) gain optimization.

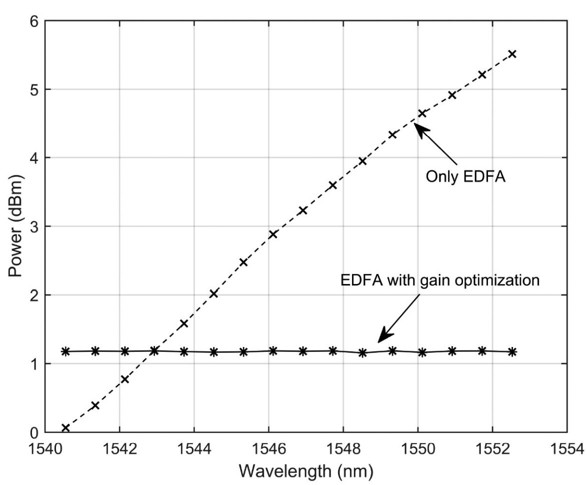


Fig. 7. Optical power versus wavelength analysis for EDFA amplification without and with gain optimization.

at 5 km the total attenuation of the link is maximum for hilly areas of Srinagar at 12.4 dB while the coastal areas of Chennai witness the least attenuation of 2.5 dB, meanwhile the plain areas of Chandigarh and desert areas of Jodhpur recorded 9.5 dB and 5.5 dB of attenuation, respectively. Hence, we can conclude that the total attenuation (in dB) of the FSO link for a particular location depends entirely on the atmospheric conditions of the location. Consequently, the variability in total attenuation of FSO link for different locations has been observed in Fig. 8(a). The proposed link has been designed with a transmission power of 10 dBm and Fig. 8(b) analyses the variations in received power for different locations of India. Incoherence with results shown in Fig. 8(a), we observe that received power is maximum for the coastal location of Chennai due to lesser fog weather conditions, while the hilly area of Srinagar recorded maximum power dip owing to extreme weather conditions. At 5 km, the received power for Chandigarh, and Jodhpur is -16.9 dBm and -12.9 dBm respectively. As the various geographical locations of India experience different atmospheric conditions as well as different channel losses, the received power has also witnessed variability as depicted in Fig. 8(b). Fig. 8(c) illustrates the variation of the proposed system design's signal-to-noise ratio (SNR), for different locations of India, as the link range is varied from 1 km to 5 km. As expected, due to highly favorable link conditions, Chennai records the maximum SNR i.e. 31.56 dB for a link range of 5 km, while Srinagar witnesses a minimum SNR of 23.3 dB due to intense fog conditions for the same link range. The bit error rate (BER) performance of the proposed FSO communication system for various regions of India has been shown in Fig. 8(d). The BER performance of the proposed system design degrades with an increase in transmission distance. The coastal area of Chennai has witnessed the best BER performance amongst the considered locations. For a benchmark BER of 10^{-9}, a link range up to 10.75 km can be achieved in the coastal area of Chennai while for the similar condition the link range in the hilly area of Srinagar reduces to 5.3 km due to reduced visibility conditions. Similarly, the maximum achievable link ranges in the case of the plain area of Chandigarh and desert area of Jodhpur are 6.53 km and 7.85 km, respectively ensuring a BER of 10^{-9}. The holistic comparison of FSO link performance across different geographical locations of India in terms of received power, SNR and BER has been compiled in Table III and Table IV. Table III shows the maximum achievable link ranges under average fog weather conditions for India's various locations. From Table IV it can be seen that for the link distances from 1 km to 5 km, the proposed FSO system has

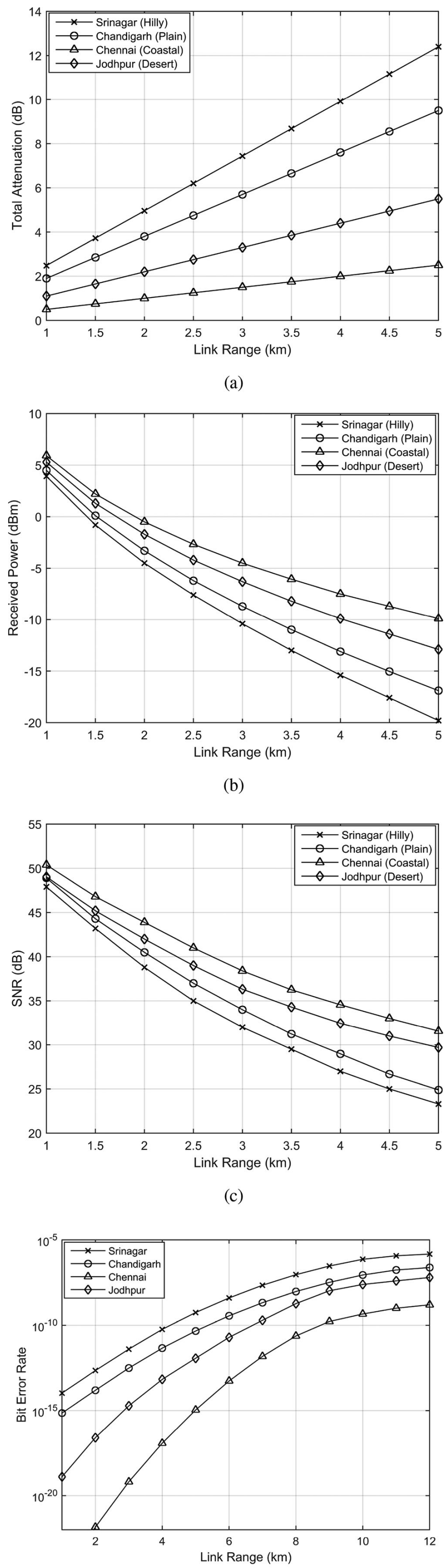


Fig. 8. For different geographical locations of India, analysis of (a) attenuation vs. link range (b) received power vs. link range (c) SNR vs. link range (d) BER vs. link range.

TABLE III
MAXIMUM ACHIEVABLE FSO LINK RANGES FOR VARIOUS GEOGRAPHICAL LOCATIONS IN INDIA FOR REFERENCE BER OF 10^{-9}

Location	**Attenuation** (dB/km)	**Maximum Link Distance** (km)	**BER**
Srinagar (Hilly)	2.48	5.3	10^{-9}
Chandigarh (Plain)	1.9	6.53	10^{-9}
Jodhpur (Desert)	1.1	7.85	10^{-9}
Chennai (Coastal)	0.5	10.75	10^{-9}

delivered the best performance in the coastal area of Chennai but significant performance degradation is observed in the hilly area of Srinagar, whereas the desert area of Jodhpur fairs slightly better than the plain area of Chandigarh.

Fig. 9 demonstrates the constellation plot of the proposed system design at different stages of the DSP module. Constellation plots are qualitative factors to determine the severity of channel conditions and receiver reliability, the more the clutter-free constellation better the system is. In our case use of the DSP module at the receiver has been undertaken to compensate for phase, frequency, and timing errors in the received signal which would have otherwise lead to overlapping constellations and thus increased BER. Fig. 9(a) depicts the severe distortion of the data signal, before the DSP module, as the constellation points are overlapping and thus making the detection of information signal difficult. As the deteriorated signal is processed by the adaptive equalization stage of the DSP module, the degrading effects of the atmospheric channel have reduced comparatively as the constellation points have demonstrated a reduction in interference, as shown in Fig. 9(b). The scattering of constellation points has further increased after processing of the received signal by the FOE stage of the DSP module as shown in Fig. 9(c). Furthermore, the channel-induced effects, like phase shift, are further reduced by the CPE stage of the DSP module, illustrated in Fig. 9(d). Hence, the DSP module has significantly compensated for the channel impairments and improved the performance of the proposed system design by increasing the reliability of detecting the information signal. Fig. 10 represents the constellation plots of the proposed FSO system design for cities of Srinagar, Chandigarh, Chennai, and Jodhpur, respectively at a link range of 5 km. Further analysis of Fig. 10(c) and Fig. 10(d) indicate that for different cities and geographical locations considered here, Chennai and Jodhpur have pretty clear and separated constellation points however, in the case of Srinagar and Chandigarh where link conditions are very severe, the separation between constellation points becomes jittered, as depicted in Fig. 10(a) and Fig. 10(b), respectively.

Table V outlines the comparison of our proposed system design with the previous works. The proposed high-speed system design, based on realistic and practically safe link parameters, has shown promising results for diverse geographical locations of India to support 5G mobile networks and smart city infrastructure. The proposed system has delivered significant and practically achievable link distances, ranging from 5.3 km to

TABLE IV
PERFORMANCE ANALYSIS OF PROPOSED 16-CHANNEL WDM BASED ODFM-FSO SYSTEM FOR VARIOUS GEOGRAPHICAL LOCATIONS IN INDIA

Link Range (km)	**Parameter**	**Srinagar (Hilly)**	**Chandigarh (Plain)**	**Jodhpur (Desert)**	**Chennai (Coastal)**
1	Received Power (dBm)	3.9	4.5	5.3	5.9
	SNR (dB)	47.9	48.9	49.04	50.39
2	Receiver Power (dBm)	-4.5	-3.3	-1.7	-0.5
	SNR (dB)	38.8	40.5	42	43.89
3	Receiver Power (dBm)	-10.4	-8.7	-6.3	-4.5
	SNR (dB)	32	34	36.32	38.4
4	Receiver Power (dBm)	-15.4	-13.1	-9.9	-7.5
	SNR (dB)	27	28.98	32.45	34.56
5	Receiver Power (dBm)	-19.8	-16.9	-12.9	-9.9
	SNR (dB)	23.3	24.89	29.7	31.56

TABLE V
COMPARISON OF PROPOSED SYSTEM WITH PEER LITERATURE WORKS

Parameter	[23]	[24]	[26]	[28]	[29]	[31]	[33]	[11]	**Proposed Design**	**Proposed Novelty**
Transmitted Power (dBm)	$\mathcal{NS}$	4	10	25	50	10	33	40	10	Safe & practical transmission power
Number of Channels	1	8	1	4, 8, 16	16	8	1	32	16	16-Channel WDM-FSO system inherently offers higher link capacity
Maximum Data Rate ($Gbps$)	$\mathcal{NS}$	80	1.25	24.96	16	80	10	80	160	160 $Gbps$ optical link for supporting *5G* applications
Channel Spacing (GHz)	$\mathcal{NA}$	$\mathcal{NS}$	$\mathcal{NA}$	$\mathcal{NS}$	$\mathcal{NS}$	100	$\mathcal{NA}$	100	100	Optimized channel spacing
Modulation Type	$\mathcal{NS}$	16-QAM + OFDM	NRZ based OOK	NRZ based OOK	NRZ based OOK	DPSK	16-QAM, QPSK	NRZ based OOK	16-QAM + OFDM	Advanced modulation techniques implemented
Authenticated Meteorological Data source	NO	NO	NO	NO	NO	NO	NO	NO	YES	Statistical Data has been sourced from Meteorological Department of India
Geographical Locations	$\mathcal{P}$, $\mathcal{C}$	$\mathcal{P}$	$\mathcal{C}$	$\mathcal{P}$	$\mathcal{D}$	$\mathcal{NA}$	$\mathcal{NA}$	$\mathcal{NA}$	$\mathcal{H}$, $\mathcal{P}$, $\mathcal{C}$, $\mathcal{D}$	Diverse geographical locations of India have been evaluated
Maximum Link Range (km)	$\mathcal{NS}$	2	$\mathcal{NS}$	345	13.5	3	180	950	10.75	Acceptable and practical link range for last mile applications
Gain Optimization	No	No	No	No	No	No	No	No	Yes	Gain optimization has ensured constant power levels across each channel of the proposed link
DSP Module	$\mathcal{NA}$	$\mathcal{NA}$	$\mathcal{NA}$	$\mathcal{NA}$	$\mathcal{NA}$	$\mathcal{NA}$	$\mathcal{NA}$	$\mathcal{NA}$	YES	DSP module ensured reliable recovery of message signal

Acronyms: $\mathcal{NA}$: Not applicable, $\mathcal{NS}$: Not specified, $\mathcal{P}$: Plains, $\mathcal{C}$: Coastal, $\mathcal{H}$: Hilly, $\mathcal{D}$: Desert

10.75 km, for potential areas of India by operating at an overall data transmission rate of 160 Gbps. In addition to this, the robustness of the proposed system design has been evaluated by considering the actual and real-life based meteorological data related to atmospheric conditions of hilly, plain, coastal, and desert areas of India. The use of advanced modulation schemes like 16-QAM and OFDM techniques along with the use of gain optimization and DSP module has further enhanced the immunity of the proposed system design against severe atmospheric channel conditions like inter-symbol interference and unwanted phase shift in contrast to other modulation techniques like NRZ based OOK, DPSK and QPSK.

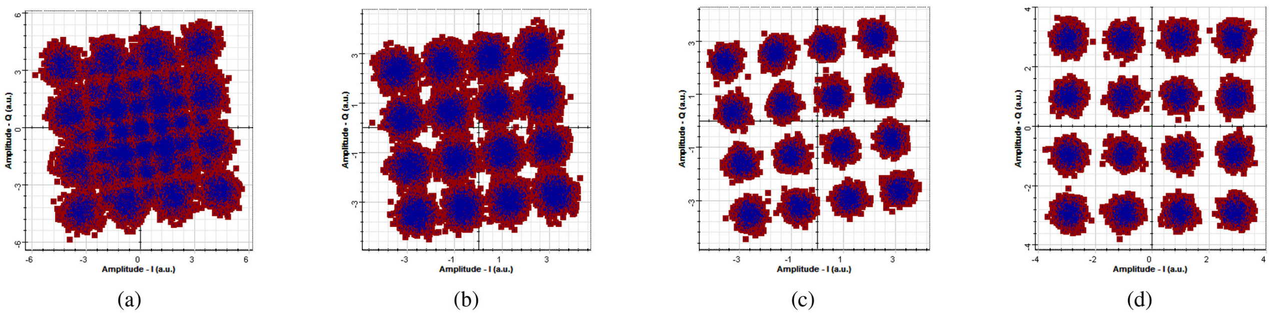


Fig. 9. Constellation diagrams of proposed system design: (a) before DSP module. (b) after adaptive equalization stage. (c) after FOE stage. (d) after CPE stage.

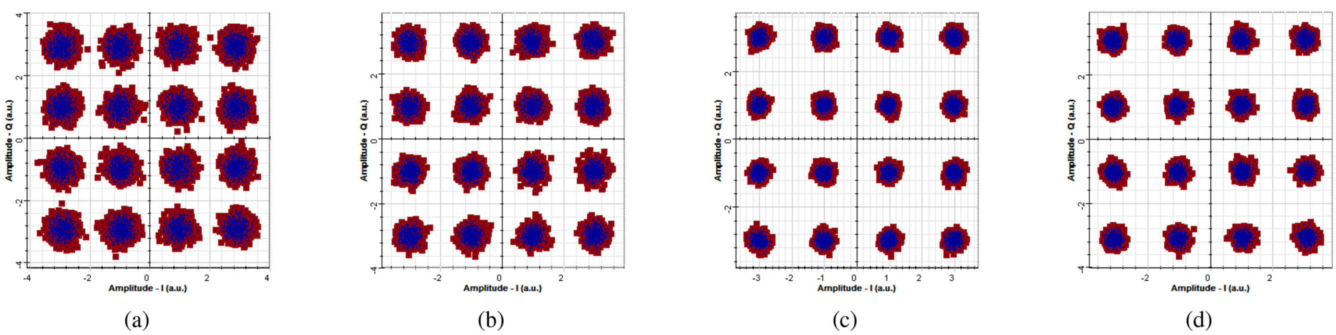


Fig. 10. Constellation diagrams of proposed 16-channel WDM based OFDM-FSO system at a link distance of 5 km for (a) Srinagar (Hilly), (b) Chandigarh (Plain), (c) Chennai (Coastal), and (d) Jodhpur (Desert).

V. Conclusion

The proposed FSO link discussed here is capable of delivering data transmission rates of up to 160 Gbps which will be indeed very significant in the light of the evolution of 5G infrastructure for high speed data services in India. The link investigated here has been modeled considering actual link adversities across diverse geographical locations of India and practical link design parameters. In addition to this, advanced modulation schemes have been used to improve spectral efficiency and link immunity against channel imperfections. The regions targeted for this study are the hilly, plain, coastal, and desert areas of India. The coastal area of Chennai has recorded maximum average visibility among all locations and on the other hand, the hilly area of Srinagar has witnessed reduced average visibility as compared to other locations. Consequently, the maximum achievable link range of 10.75 km at a reference bit error rate of 10^{-9} is achievable in coastal area of Chennai and can meet the high bandwidth requirements of future 5G mobile networks and smart city infrastructure. On the other hand, FSO links of ranges 6.53 km and 7.85 km in case of plain area of Chandigarh and desert area of Jodhpur at reference bit error rate of 10^{-9} can support the existing network infrastructure in handling exponentially rising data traffic and facilitating connectivity between various devices and users using future generation mobile networks. Although, the hilly area of Srinagar has recorded the shortest FSO link of the range 5.3 km, the problem of installation of optical fiber network due to mountainous and difficult terrain can be solved by installing FSO links with hybrid RF/FSO backup system in case of severe atmospheric conditions. Moreover, the gain optimized EDFA-based amplification has resulted in favorable amplification of FSO signals ensuring constant power levels across different channels. In addition to this, the advanced modulation schemes and coherent detection of FSO signals along with the use of digital signal processing modules have further reduced the degrading effects of atmospheric conditions and enhanced the system performance. Hence, the proposed FSO system design can facilitate the realization of 5G cellular services in diverse geographical locations of India and can provide high-speed data services in upgrading the current infrastructure of cities of India to advanced infrastructure based on future generation mobile networks and IoT technology.

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