S. Magidi* and A. Jabeena

Review on Wavelength Division Multiplexing Free Space Optics

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Abstract: Wavelength division multiplexing-based free space optics (WDM FSO) has emerged as a potential communication network candidate for last-mile access among other applications. FSO has received much attention in the last few years as a complement as well as an alternative to radio frequency-based communication due to spectrum crisis among other reasons. On the other hand, WDM has been considered as one of the next-generation optical access network candidates for bandwidth efficiency and increased data rates. A hybrid network of these two technologies thus has emerged as another research direction. In this article, we present the background, progress and the current state of WDM FSO.

Keywords: FSO, WDM, modulation, hybrid, spectrum slicing, broadband

1 Introduction

The use of bandwidth hungry applications has been on the increase in recent years, resulting in bandwidth bottleneck especially at the access network side. Even so, the number of mobile devices connected to the network continues to grow because wireless data services are almost becoming a necessity. Cisco 2014 forecast on global mobile data traffic issued that most probably by the year 2018, more than two-thirds of the world total traffic data will be video [1], prompting users to require in excess of 30 Mbps guaranteed bandwidth. Some of the causes of increased bandwidth demand include video on demand, high-definition (HD) TV, cloud computing online gaming, e-learning and online user-generated video content. Notably, most online multimedia streaming, gaming and surveillance are adopting HD [2]. Data sharing in various multimedia services such as audio on demand, video on demand and peer to peer stimulates the necessity of higher bandwidth provisioning. Obviously, such huge bandwidth demand prompts innovative and inexpensive techniques which can provide higher aggregate bandwidth at the same time being scalable, which is the main limitation of the currently deployed radio services. This has forced research to look for alternative technologies and techniques which can supplement as well as coexist with RF networks. Higher data rates can be achieved by either increasing spectral efficiency or moving to millimeter wave band [3]. Because the radio frequency (RF) spectrum has been congested, alternatives such as free space optics (FSO) and millimeter wave communication band are being explored. Meanwhile, wavelength division multiplexing (WDM) passive optical network has secured a winning proposal for next-generation access networks. In this article, we present the background, current state and future of WDM FSO as a way of further increasing the bandwidth capacity.

The rest of the article is organized as follows: in Section 2, the FSO communication is discussed, followed by FSO atmospheric channel models in Section 3. WDM has been discussed in Section 4, followed by WDM FSO in Section 5. WDM FSO design challenges and mitigation techniques have been discussed in Section 6 and Section 7, respectively. Some achievements in WDM FSO by some researchers have been considered in Section 8. Current advances in WDM FSO have been discussed in Section 9. Finally, concluding remarks are in Section 10.

2 Free space optics communication

Free space optics is a line of sight communication systems using air or vacuum as the medium of propagation. It uses unguided media to potentially offer wide bandwidth and at the same time supporting high data rate, comparable to the optic fiber, making it highly attractive in meeting the increasing broadband traffic. The first, second and third transmission windows are normally used, corresponding to 850 nm, 1300 nm and 1550 nm [4]. The existence of FSO communication system can be traced as far back as 1876 [5], when Alexander Graham Bell demonstrated the first telephone system that worked by converting sound

***Corresponding author: S. Magidi,** School of Electronics Engineering, Vellore Institute of Technology, Vellore 632014, India, E-mail: magidisimbarashe37@gmail.com
A. Jabeena, School of Electronics Engineering, Vellore Institute of Technology, Vellore 632014, India

waves into electrical signals that could be transmitted in free space for 213 m. Appreciable use of FSO was in military communication even during World War I and World War II driven by the failure and unavailability of wired telephone line communication. However, great advancements in FSO technology awaited the invention of the first working laser in 1960 [6], with particular interest in military organization. Still sooner than later, the technology lost momentum due to the widespread deployment of the then fiber optic communication that was invented at the same time as the laser. It is only in recent years that the research and exploration in FSO communication was revived, receiving much attention, the key drivers being unprecedented exponential increase in the bandwidth and capacity requirements, leading to the RF congestion [7, 8]. Hence, the shift from RF to optical communication.

2.1 Advantages of FSO

1. Unlicensed spectrum: Because the RF spectrum suffers from electromagnetic interference and is congested, it implies that interference is a major problem, hence the need of spectrum licensing by the government to avoid that. Since there is no electromagnetic interference in FSO, till now, it is unlicensed by the governments or other authorities. This reduces the deployment time [7].
2. High data rate can be supported: The optical carrier frequency is high, leading to large bandwidth. Furthermore, it is reported that already there are transceivers that can support Gb/s data rates [9].
3. Easy of deployment: FSO installation does not involve digging of trenches and hence right of way does not exist. The installation takes less times when compared to fiber optic cable or RF communication link [10].
4. Possibilities of using spatial multiplexing and full-duplex operation.
5. High security: The optical beam is immune to radio interference, is highly directional, has narrow-beam divergence and cannot penetrate the walls. Furthermore, methods used in eavesdropping RF signals such as spectrum analysis are difficult to apply in order to detect FSO beams.
6. Cheaper components which also consume less power.
7. Upgrading of the system can also be easily done. The components are light in weight and compact. FSO also finds applications where fiber optic communication is impossible.

Despite these numerous benefits, in terrestrial networks, FSO is predominantly limited to a span of few kilometers dues to the existence of atmospheric turbulence and prevailing adverse weather conditions. The atmospheric turbulence results in stochastic fluctuations of the received laser beam, increasing the bit error rate (BER), and hence compromising the FSO link [11]. Transceivers are typically installed on building tops, further contributing to misalignment or pointing errors, due to building sways caused by dynamic meteorological parameters such as air temperature, wind speed and pressure [9]. The range of FSO is limited by degradation caused by fog, beam dispersion, atmospheric absorption, rain, snow, shadowing and pollution. Nonselective scattering is considered as one of the main drawbacks of FSO, especially in tropical countries. To mitigate these challenges, some of the techniques that have been proposed include careful choice of modulation formats, multiple input and multiple output (multibeam concept), aperture averaging and WDM. Furthermore, some state-of-the-art transceivers include large fade margin.

To date, well-known typical applications of FSO include but not limited to (1) LAN to LAN connectivity at Ethernet or Gigabit Ethernet speeds. This is usually extended to connections in the city or metropolitan area network or intercampus connections. (2) Short-lived network connectivity for events such as conferences, meetings and celebrations or disaster management. In such cases, it is used as a backbone for or to coexist with ad-hoc networks. As an example, during 2010 FIFA World Cup, UK TV station BBC deployed FSO links for Ethernet-based transport of HD video between temporary studio locations set up in Cape Town, South Africa (3). Alternative or coexistence with existing wireless and wireline technology. (4) Inter- and intrachip communications in data centers. (5) Last-mile connectivity: These are the links that reach the end user. They can be deployed in point-to-point, point-to-multipoint, ring or mesh connections. (6) Backup for fiber optic connection: In fiber optic deployment for business applications, an extra fiber cable is installed as a backup to avoid complete outage. Hence, FSO can be used in such a scenario. (7) Cellular backhaul or in base station-to-base station connectivity.

The semiconductor Inter-Satellite Laser Experiment (SILEX) research program was a result of the OWC inter-satellite link by the European Space Agency (ESA) in the mid-1980s. Another inter-satellite optical wireless link was demonstrated by the SPOT-4 French Earth observation in sun synchronous low earth orbit, which had a data capacity of 50 Mbps. This was demonstrated in the year 2001 [8]. The improvement in data capacity to Gbps was further enhanced by the application of coherent modulation techniques [12–14]. In particular, the Mars Laser Communications. Demonstration aims at demonstrating optical communications from Mars to the Earth at data rates between 1 and 10 Mbps [15]. Another recent NASA initiative known as Laser Communication Relay Demonstration project aims to demonstrate the deployment of OWC links for inter-satellite transmission in deep space and deep space-to-Earth. Currently, Free Space Optical Networking Architecture (FSONA) is one of the leading companies that manufacture and supply FSO transceivers. It manufactures FSO transceivers able to support data capacity of 2.5 Gbps. In another deployment to the Credit Agricole French Bank, four 2.5 Gbps links were deployed instead of a fiber optic cable for their new building in Paris. It is also reported that FSONA provides mobile cellular communication backhaul services for LTE fourth generation to customers with a link capacity of 1.25 Gbps [16]. Meanwhile, Northern Storm, another FSO company in the US, is reported to have installed a hybrid FSO/RF link in California city with a capacity of 10.31 Gbps and RF with a 1 Gbps as backup. However, the link range is limited to just 288 m although the link availability is very high.

3 Channel models

Since FSO uses laser beam that propagates in unguided media, the free space channel needs to be characterized in order to be able to predict and understand beam interaction with channel and exponentiation. In reality, the channel conditions are constantly varying due to turbulence, making it hard to have a constant link availability. Hence the need of a channel model to try and predict the BER as a function of various atmospheric parameters. Deep fade results in temporary failure of the FSO link due to acute drop in SNR. In particular, if a deep fade lasts for ~ 1–100 μs on the multiple Gbps optical channel, up to 10^9 consecutive bits might be lost which indeed is severe [17]. In this section, we shall briefly discuss on the major channel models that have been widely used to characterize the laser beam propagation in free space.

3.1 Log-Normal distribution

The PDF of the log-normal channel distribution is expressed as [18]:

$$p(I) = \frac{1}{\sqrt{2\pi\sigma_1^2}}\frac{1}{I}exp\left\{-\frac{\left(In\left(I/I_0\right)+\frac{\sigma_1^2}{2}\right)^2}{2\sigma_1^2}\right\} \tag{1}$$

I_o is the irradiance in the absence of atmospheric turbulence, σ_1^2 is the scintillation index. This model is valid for weak turbulence $C_n^2 = 5 \times 10^{-17}$, over short distances (order of hundreds of meters) [18]. The Royton variance is given by: $\sigma_1^2 = 1.23C_n^2k^{\frac{7}{6}}L^{\frac{11}{6}}$ where C_n^2 is the refractive index structure, which characterizes the turbulence strength and k is the wave number.

3.2 Negative exponential model

The model is used for stronger turbulence conditions and for several kilometers [19].

$$p(I) = \frac{1}{I_o}exp\left(-\frac{I}{I_o}\right) \tag{2}$$

$I_o > 0$ is the mean irradiance.

3.3 Gamma–Gamma channel model

Gamma–Gamma modeling partitions the normalized light intensity into small-scale and large-scale eddies, with both small-scale and large-scale eddies following the Gamma distribution, Mathematically, the PDF of the Gamma–Gamma fading model is expressed as [20]:

$$p(I) = \frac{2(\alpha\beta)^{\frac{\alpha+\beta}{2}}}{\gamma(\alpha)\gamma(\beta)}I^{\frac{\alpha+\beta}{2}-1}K_{\alpha-\beta}\left(2\sqrt{\alpha\beta I}\right), I > 0. \tag{3}$$

α and β denote the effective numbers of large-scale and small-scale eddies, respectively, $K_n(.)$ is the modified Bessel function of second kind of order $(\alpha - \beta)$ and $\gamma(.)$ is the Gamma function. The effective numbers α and β are given as:

$$\alpha = \left[\frac{0.49\sigma_R^2}{\left(1+1.11\sigma_R^{\frac{12}{5}}\right)^{\frac{5}{6}}}\right] - 1 \tag{4}$$

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

The overall system performance can be improved by selecting the optimal modulation scheme in radio over FSO system by transmitting an OFDM signal in Gamma–Gamma [21].

3.4 K distribution

The K distribution PDF results as a product of exponential distribution and the Gamma–Gamma distribution, and is useful for modeling strong turbulence atmospheric conditions. It is also a special case of the Gamma–Gamma model when $\beta = 1$. Its PDF is expressed as [22]:

$$p_{I_{mn}}(I_{mn}) = \frac{2\alpha_{mn}^{\frac{\alpha_{mn}+1}{2}}}{\Gamma(\alpha_{mn})} I_{mn}^{\frac{\alpha_{mn}-1}{2}} K_{\alpha_{mn}-1}\left(2\sqrt{\alpha_{mn} I_{mn}}\right) \tag{6}$$

where $_{mn}$ is the parameter related to the discrete number of scatters, $K_v(.)$ is the modified Bessel function of second kind of order v and $\Gamma(.)$ is the Gamma function. Another recent one is known as Malaga channel model or simply the M model [23]. Such a distribution model is based on the distinction of three optical components in the propagation of the signal: (1) the line of sight component, (2) the classic scattering field independent of the line of sight and (3) the scattering contribution coupled to the LOS field term. Furthermore, this model unifies all models mentioned above and takes care of pointing errors. Further details can be found in [24, 25] and the references therein.

3.5 Weather-induced losses

Adverse weather results in exponential extinction h_L of the information carrying laser beam, described by Beer–Lambert law as [26];

$$h_L = e^{-\sigma L} \tag{7}$$

where L is the link length and σ is the atmospheric attenuation coefficient given by:

$$\sigma = \frac{3.91}{V}\left(\frac{\lambda}{550}\right)^{-q} \tag{8}$$

where λ is the wavelength in mm, V is the visibility in (km), and q is the distribution size of particles obtained from Kim–Kruse model. The value of q is 1.6 for $V \geq 50$ km, 1.3 for 6 km $\leq V \leq 50$ km and $0.585V^{\frac{1}{3}}$ for $V \leq 6$ km [27].

4 Wavelength division multiplexing

Probably well known in fiber optic communication, WDM is a method of utilizing the high bandwidth carrier of the channel by allocating each communication channel a different wavelength multiplexed onto a single channel. Wavelengths are spatially separated at the destination to different receiver locations. It has been considered as the next-generation alternative technology to fulfil future requirements of (PONs) access networks for scalable aggregate bandwidth provisioning. The capacity of system can be increased simply by increasing the number of channels and tightening the channel spacing without using more than one FSO link [11]. Because of the rapid increase in bandwidth demand in WDM-based access, WDM is a potential solution for future data transport with regard to all-optical wide area networks. The following are benefits that it offers;

- Large capacity
- Reduced optical path loss
- Channel independence
- Format transparency
- Network security and scalability
- Protocol transparency
- Easy upgradability

Hence, it seems noble to combine the advantages offered by WDM and those offered by FSO to come up with a hybrid system known as WDM FSO. Such a system greatly enhances the data capacity of the network.

5 Wavelength division multiplexing free space optics (WDM FSO)

Although FSO systems and WDM systems have been independently well studied separately, the continued demand for bandwidth has seen the convergence of the two technologies becoming a new study area [9]. In such hybridization scheme, WDM scheme conveys data over free space to enhance bandwidth utilization for broadband applications. In recent years, the data-carrying capacity of WDM has reached orders of terabits per second and it can be easily integrated with FSO to considerably increase the bit rates [28]. Thus, WDM-FSO is therefore a promising solution to meet the exponential growth in the global demand for broadband services [29]. In literature, several WDM FSO architectures have been proposed and demonstrated. WDM PONs using FSO in the distribution network to support multiple users have also been proposed [9]. Practically, FSO can be an extension of optical fiber communication link since they both share the same transmission wavelength and system components. FSO can be made to be fully compatible with optical fiber communication, using a pair of FSO terminals which can be transparently connected to single-mode fiber [30]. The basic idea of WDM FSO is portrayed in Figure 1.

Typically, input data which is a pseudorandom sequence is converted to electrical form by line coding

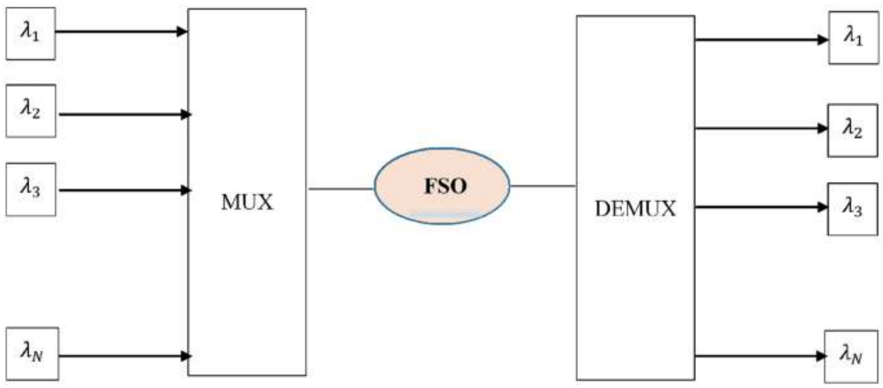

Figure 1: Schematic of a WDM FSO system.

scheme, such as nonreturn to zero (NRZ) or return to zero (RZ). External optical modulation is preferred to direct modulation, since it supports a longer distance. This becomes the input to the Mach–Zehnder optical modulator, with the other input being the continuous-wave (CW) laser source. The output of the Mach–Zehnder modulator is a modulated signal, which is multiplexed with other signals from other transmitters by the multiplexer. The signal is propagated through the free space optical channel. At the receiver, demultiplexing is done, and either a PIN or Avalanche Photodiode (APD) photodetector is used in recovering electrical signal from the optical signal. This is normally followed by a low-pass electrical filter, which removes excess noise. A low-pass Bessel or Gaussian filter is usually employed. On–off keying (OOK) and Non-Return to Zero (NRZ)/Return to zero (RZ) Differential Phase Shift Keying (DPSK) modulation formats have been considered and compared in terms of end-to-end BER, link distance and data rate supported in [31]. Eight channels were used and the geometric losses were not considered.

6 WDM FSO system design considerations (challenges)

The receiver typically has a minimum sensitivity to guarantee reliability of the FSO link. The goal is to maintain the received power above the receiver sensitivity. It is important to note that the signal loss between the transmitter and the receiver varies randomly over time according to the instantaneous prevailing weather conditions [32]. Hence, the design needs to factor this into account for reliable communication design. Well-known weather conditions that affect adversely the FSO communication is rain and haze conditions. The atmospheric losses in the atmosphere are broadly classified into two categories. (1) Attenuation: in this case, the signal energy is absorbed by the particles present in the atmosphere. Gases in the atmosphere such as O_2 and N_2 and water vapor lead to molecular absorption. (2) Scattering: in this process, the laser beam colliding with particles in the atmosphere is redirected leading to redistribution of light and consequently deflection in the arrival angle. Rayleigh scattering is when the size of the scattering particles is less than the wavelength of the propagating laser beam. On the other hand, if the size of the scattering particles is comparable to that of the wavelength of the laser beam, this leads to Mie scattering. Nonselective scattering is when the scattering particle size is significantly larger than the wavelength of the laser beam [33].

6.1 Rain

Laser power is greatly attenuated by rain in a practical FSO communication system [34]. Visibility is also reduced by installation characteristics besides rain. Mathematical models exist that give the relationship between the rainfall parameters and the general signal loss. Hence, the link loss due to rain and other weather phenomenon are geographic dependent. To characterize fully the link loss for a given place, the local weather conditions such as rainfall and wind speed and direction are factored into the model. The attenuation of the laser beam in the free space channel is given by Beers law as: $T(R) = \frac{P(R)}{P(O)} = e^{-\beta R}$ where R is the link range, $T(R)$ is the transmittance at range R, $P(R)$ is the laser power at range R and $P(O)$ is the transmitter laser power, with β being the scattering coefficient. These scattering particles are large enough that angular distribution of the scattered radiation can be described by geometric optics. In the event that the scattering does not depend on the wavelength of the laser beam, then it is called selective scattering. Hence, the scattering coefficient β can be calculated from [35] as $\beta = \pi a^2 N_a Q_{scat} \left(\frac{a}{\lambda}\right)$, where a is the drop radius, which normally lies between 0.001 and 0.1cm, N_a is the rain drop distribution with Q_{scat} being the scattering efficiency, and λ is the wavelength. Further, the raindrop distribution is given as [36]: $N_a = \frac{Z_a}{4(\pi a^3)V_a/3}$, with Z_a being the rainfall rate.

6.2 Haze

Attenuation value is a function of the visibility level. Haze refers to a situation in which the particles stay suspended in the atmosphere longer, thus it presents serious degradation to FSO link. In a way to predict the system performance under haze conditions, two methods exist. The first which is a little bit tough involves installation of the FSO hardware temporarily and analyzing the performance to assess whether it satisfies the minimum requirements or not. If the system underperforms, the necessary adjustments are done to the hardware and if need be, further corrective action is taken. This is typically done on the site. The second method involves prediction of the haze degradation by factoring in the weather parameters in the model. A commonly used model is Kim and Kruse model [26], expressed as in eq. 8. The size distribution of the scattering particles is given in Table 1.

6.3 Beam divergence

As the laser beam propagates in the FSO channel, it will expand from its beam waist. In FSO communication, a low beam divergence is desirable, with the requirement that the divergence angle of the transmitted beam should match the receiver telescope (antenna) field of view (FOV). The relationship between the divergence angle θ, laser wavelength λ and the telescope aperture size D_r is given as $\theta = \frac{\lambda}{D_r}$. Hence, the aperture diameter of the telescope needs to be adjusted accordingly, in order to improve receiver sensitivity.

6.4 Fog

The density of fog varies depending on the particle size and height, making it difficult to model. It causes both scattering and absorption. The attenuation coefficient due to fog is similarly given by eq. 8 above, i.e. $\alpha_{fog} = \frac{3.91}{V}\left(\frac{\lambda}{550}\right)^{-q}$

Dense fog might lead to complete outage [37], and hence the need to switch to RF link [38]. Increasing transmitter power will improve the system performance in light fog, but the improvement is minor in dense fog [39]. Furthermore, a study carried out in [40] showed that a BER of 10^{-3} was obtained over 1 km with 600 m visibility range. However, under dense fog, the same BER of approximately 10^{-3} was obtained over a 200 m link range . This makes channel modeling in fog a complex task.

Table 1: Size distribution of scattering particles.

q	Type of visibility	Length of visibility (km)
0.585	Low	$V < 6$
1.3	Average	$6 < V < 50$
1.6	Very high	$V > 50$

6.5 Snow

The attenuation effects of snow are somehow between that of rain and fog since its particles lie in between these two. In desert countries, sand is also another significant source of scattering of FSO laser signals.

6.6 Misalignment errors/Pointing errors

Some of the well-known causes of misalignment errors include earthquakes, building sways, wind and vibrations. A wide divergence angle for the laser is desirable for short-link applications, while narrow divergence laser must be used with an automatic tracking system of some sort [41].

6.7 Beam wandering

Beam wandering, as well as the scintillation index, is an important characteristic of the radiation determining its utility for practical applications. In the event that the size of the refractive index of the cells exceeds the beam size, then scattering of the beam occurs. Such an effect increases with distance and scintillation index due to beam wandering is given as:

Table 2: Laser beam attenuation in different weather conditions.

Weather condition	Attenuation α(dB/km)
Clear air	0.43
Haze	4.2
Moderate rain	9.2
Heavy rain	9.2
Light fog	12
Moderate fog	20
Heavy fog	42.2

$$\sigma_r = 1.83\lambda^{-\frac{1}{6}} C_n^2 L^{\frac{17}{6}} \tag{9}$$

Effect of beam wander is more pronounced for shorter wavelength than longer wavelength.

6.8 Beam spreading

The spreading of the beam as it propagates in the atmosphere is generally known as beam spreading and results in the beam being diffracted at the receiving aperture. It can also be a result of the atmospheric turbulent when the beam size is larger than the eddy cells. The effective radius is given by:

$$\alpha_{eff} = 2.01\lambda^{-\frac{1}{5}} C_n^{-\frac{6}{5}} L^{\frac{8}{5}} \tag{10}$$

6.9 Background noise

The exposure of the receiver to direct or indirect sunlight or artificial lights leads to background noise. The sources of background noise are ambient light sources such as the sunlight, moonlight and fluorescent light. Such noise contribution is normally modeled as zero mean white Gaussian. This noise affects receiver sensitivity. Background noise reduces the signal-to-noise ratio gain and can be eliminated through bandpass filter before photodetection [42] and also a careful selection of the wavelength, generally around 1550 nm. Further, it can also be reduced by double transmission and differential mode data detection methods [43].

6.10 Eye safety

There is a tradeoff between the laser power needed to support high data rate especially under severe weather conditions and the human eye safety concerns. Laser power that exceeds a ceiling threshold has harmful effects to the human health especially the eye. Hence, different governing bodies have enforced a limitation on laser power in optical wireless communication systems, such as the ANSI ZI 36.1 and IEC 60825-1, which works to protect the human body exposure to excessive laser radiation. The performance of FSO systems are degraded by the safety regulations, i.e. the constraints on transmit power. Operating low-power sources requires the availability of highly sensitive receivers, which may suffer from more interference from the environment [2].

7 Mitigation techniques in WDM FSO systems

7.1 Advanced modulation techniques

Although OOK-based modulation schemes have been used because of its simplicity and cost-effectiveness, several other advanced modulation schemes are employed with success in FSO to mitigate turbulence effect according to the required energy efficiency, target spectral efficiency such as pulse position modulations (PPM) [44], multiple PPM [32], pulse width modulation [45], digital pulse interval modulation [46] and binary phase shift keying (BPSK) [12]. A comparative analysis of NRZ–OOK, NRZ–DPSK and RZ–DPSK in a WDM FSO communication link carried out in [31] revealed that under all turbulence conditions, from weak to strong, and at both low and high data rates, RZ–DPSK modulation-based system yielded better results than NRZ–OOK and RZ–DPSK. Even though the research did not take into account geometrical signal loss, to achieve the same BER of 10^{-11}, NRZ–DPSK could support 110 km more, which is 58% more effective. However, it has been argued [47] that DPSK-based modulation scheme might not be a cost-effective solution owing to its relatively complex transmitter design and the need of Mach–Zehnder interferometric demodulator as well as balanced detector. Hence, they recommended duobinary-based modulation schemes such as duobinary return to zero (DRZ) and modified duobinary return to zero (MDRZ), due to the flexibility of decoding and usage of simple direct detection optical receiver, thus lowering the cost of the communication system as a whole. In another study [48], a comparative study among carrier suppressed return to zero (CSRZ), DRZ, and MDRZ in a 64-channel DWDM at 10, 20 and 40 Gbps data rate concluded that MDRZ modulation scheme has better performance that others.

Furthermore, the use of forward error correction codes has been demonstrated to be a useful technique to mitigate atmospheric turbulence such as Reed–Solomon (RS) codes [49], concatenated RS codes, turbo codes [50] and low-density parity check codes [51] .

7.2 Diversity techniques

Because individual channels experience different levels of fading and interference, diversity techniques have been useful for combating the effects of atmospheric turbulence and beam scintillation. The techniques involve transmitting multiple versions of the same signal resulting in diversity gain. It has been applied in space, time, frequency or wavelength and polarization or a combination, e.g wavelength and time diversity. In all these cases, the basic assumption is that the receiver experience independent fading if placed at an appropriate distance apart. It is more effective if perfect channel state information (CSI) is known at the transmitter. In FSO communication, the system model is usually expressed as:

$$y = hx + n = \eta x I + n \tag{11}$$

where the output signal is y, with $h = \eta I$ being the intensity gain, η is the photon to electron conversion factor, x is the modulated information signal and $n \sim N(0, N_0/2)$ is the Gaussian distributed noise. With transmit diversity, the signal y can be received and processed in one of the following methods:

7.2.1 Optimal combining

In such a scenario, the different branch signals are co-phased and weighted according to their signal strength before combination:

$$P_{OC} = \int_{\bar{I}} f(\bar{I}) Q\left(\frac{1}{\sqrt{2WN_0}}\sqrt{\sum_{w=1}^{W}(h_w)^2}\right) d\bar{I} \tag{12}$$

where $\bar{I} = (I_1, I_2 \cdots I_W)$ is the vector representation of the irradiance from the W receivers.

7.2.2 Equal gain combining

Incoming signals at different receivers are combined with scaling, resulting in a PDF expressed as:

$$P_{EGC} = \int_{\bar{I}} f(\bar{I}) Q\left(\frac{\sum_{w=1}^{W}\eta_w I_w}{W\sqrt{2N_0}}\right) d\bar{I} \tag{13}$$

7.2.3 Selection combining

This scheme selects the branch with the highest SNR out of all available branches at the receiver in such a way that: $I_{SC} = max\,(I_1, I_2, \cdots I_I)$ and $SNR = max\,(SNR_1, SNR_2, \cdots SNR_I)$. The processing is such that the average BER is given by:

$$P_{I_{SC}}(I_{SC}) = \int_0^{\infty} f_{I_{SC}}(I_{SC}) Q\left(\frac{n_{SC} I_{SC}}{\sqrt{2WN_0}}\right) dI_{SC} \tag{14}$$

Such diversity schemes have been analyzed in [52] with wavelength diversity. The link range considered was 2 and 3 km and diversity order of 2 and 3 was applied, using wavelengths $\lambda_1 = 1.55$ um, $\lambda_2 = 1.31$ um and $\lambda_3 = 0.85$ um. For a target BER of 10^{-4}, the required SNR was 55 dB without diversity, whereas the same BER could be achieved at 41 dB when SC with a diversity order of 2 was used. Further, the same authors inferred that the performance could be increased by increasing the wavelength diversity order, but such an optimum diversity order was not investigated.

Multiple Input, Multiple Output (MIMO) systems with diversity techniques performs well when the CSI is well known. A system gain of 3.7 dB was realized in [53] . Also, such an improvement was realized for a ground to satellite link in [54] . Furthermore, the knowledge of CSI allows applications of transmitter control algorithms.

In another study [55], Single Input Single Output (SISO) and MIMO systems were compared over a log-normal channel of standard deviation 0.3, receiver apertures 5 cm and link distance of 2 km. Results showed that to achieve a BER of 10^{-5}, the improvement in SNR was 5 dB when two transmitters were used and 7.5 dB for three transmit apertures.

Space time block code (STBC) can also be applied in FSO for performance improvement. As an illustration, assume a flat, nonfrequency selective fading channel, with maximum likelihood detection at the receiver. Assume a WDM FSO system illustrated in Figure 2. After the data have been multiplexed, a composite data symbol vector $\bar{X}$ is mapped onto an STBC signal vector $\bar{X} = [X_1, X_2, \cdots, X_n]$, which is to be transmitted using M FSO transmitters and to be received by N FSO receivers, as shown in Figure 2.

Figure 3 shows the dependence of the average BER on average SNR for three sets of transmitter and receivers such that $(M, N) \in \{(2,1), (4,2), (8,2)\}$. It is observed that for a target BER of 10^{-5}, the average SNR required is 27 dB, 17 dB and 14 dB for the above-mentioned set, respectively. This represents a system gain of 10 dB and 13 dB by increasing the number of transmitters from 2 to 4 and from 2 to 8, respectively. Such information gives insight into the design for such STBC-coded WDM FSO systems.

7.3 Spectrum slicing

This technique has been claimed to serve a dual purpose; as a cost-effective source instead of the expensive tunable multiwavelengths sources, as well enhancing WDM FSO performance. The spectrum of a broadband source is sliced using narrow-band optical filters to achieve a unique wavelength for a channel [56]. Several methods have been tried in literature such as cascading erbium

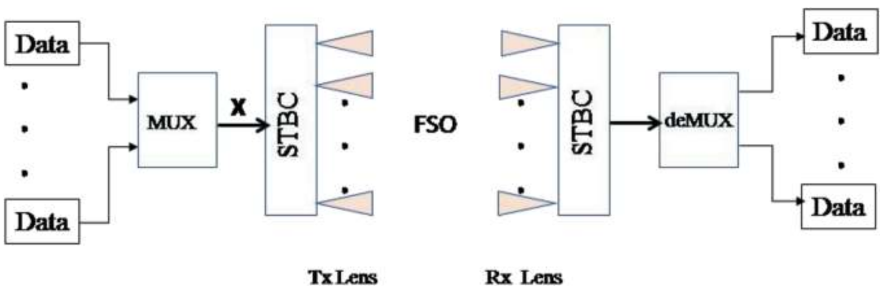

Figure 2: STBC WDM FSO system.

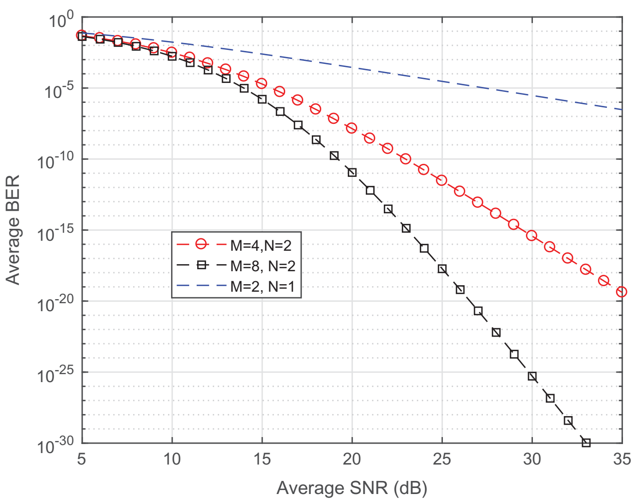

Figure 3: BER on average SNR for STBC WDM FSO.

fiber doped amplifiers (EDFA) [57], FP, superluminescent light-emitting diode and the supercontinuum generation using a highly nonlinear fiber (HNLF) [58]. The last method uses self-phase modulation effects, where for an optical signal launched in a HNLF, the resulting propagating complex field is given as:

$$E = E_0(z,t)e^{\left(\omega_0 t - (n_0 + n_2 I(z,t))k_0 z\right)} \tag{15}$$

So that the instantaneous frequency can be expressed as:

$$\omega' = \omega_0 - n_2 k_0 z \frac{\partial I}{\partial t} \tag{16}$$

Hence from eq. 16, the extra components are positioned on the pulse, effectively raising its spectral width. Such a broadened pulse can be sliced using an Additive White Gaussian (AWG). Although such schemes has been shown to enhance the link range at acceptable BER of less that 1×10^{-9} in [59, 60] and [61], the number of WDM channels was limited to 4 in all cases. More so, a narrow spectrum of the source is sliced, resulting in inadequate unbalanced power among the slices. Although an optical amplifier can be used to improve the power level, balancing or equalizing slices power remains a challenge that usually leads to cross-talk. Unfortunately, in all the above-mentioned works, this was not addressed. Several sources of noise inherent in optical broadband sources such as mode partition noise, optical beat noise and intensity noise limit SS-WDM modulation speed [62]. Such techniques can be further improved through optical amplification. In FSO, the transmission optical wavelength is chosen in the C band (around 1550 nm), since the signal suffers minimum attenuation in this band and is suitable for EDFA technology. Moreover, within its gain region, the EDFA can amplify all wavelengths simultaneously.Amplifiers used in power or

Table 3: Some work on WDM FSO to date.

Parameter	Ref [59]	Ref [60]	Ref [64]	Ref [65]	Ref [31]
Transmission mode	Single directional downlink	Single directional	Single directional	Single directional	Single directional
Transmitter Modulation formats	SS-WDM NRZ OOK	SS-WDM NRZ OOK	WDM NRZ OOK	WDM NRZ OOK Power (10 dBm) was too high	WDM NRZ DPSK
Data rate	1.56 Gbps	1.56 Gbps	1.25 Gbps	2.5 Gbps	2.5 Gbps
channel conditions	4 dB/km SISO	4 dB/km SISO	MIMO	MIMO 4 dB/km, Geometric loses neglected	SISO 0.2208 dB/km, Geometrical losses neglected
Maximum distance	2.5 km	3.3 km	1.1 km	4.75 km	190 km

Table 4: Relay performance under different scenarios [71].

	Serial		Parallel	
	1 Relay	2 Relays	1 Relay	2 Relays
DF	18.5 dB	−5.4 dB	20.3 dB	20.7 dB
AF	12.2 dB	17.7 dB	18.1 dB	20.2 dB

booster configuration and hybrid configuration have been reported to enhance greatly the performance of WDM FSO systems [63].

8 Some work done to date including techniques, data rate achieved and maximum distance in WDM FSO

In this section, we briefly present some recent achievements in terrestrial WD FSO communication systems.

From Table 4, it is clear that most research works were limited to less data rate: 1.56 Gbps in [59, 60], 1.25 Gbps in [64] and 2.5 Gbps [65]. The geometric losses were not considered in [31], hence a much longer span of 190 km was observed in [31]. But geometrical losses are expressed as $P_t/(4\pi L^2)$, where P_t is the transmitted power. This then implies that it has serious degradation impact in terrestrial FSO systems.

9 Advancements in WDM FSO

The current trends are focused on mitigating atmospheric turbulence to improve transmission link and capacity.

9.1 Adaptive transmission

A promising solution for performance improvement in FSO coins around the inherent quasistatic nature of FSO channels, which allows reliable CSI feedback to the transmitter, enhanced by the commercial availability of full-duplex FSO transceivers [66]. Adaptive transmission involves the change of system parameter such as: (1) transmit power, (2) modulation size, (3) modulation type and order, (4) code rate. A combination of these parameters maybe used also. In a Gamma–Gamma channel using Q-ary PAM, the power adaptation for channel capacity maximization has been analyzed in [67] as well as with adaptive coding in [68]. As an example, transmit power adaptation based on wavelength selection has been carried in [69], where power was allocated in a manner which enhanced the performance, thereby increasing the capacity of the system. The WDM FSO was considered to be operating by dividing the available wavelengths into a set of n nonoverlapping wavelengths $[\lambda_1 - \lambda_n]$ out of which the system could use at most m wavelengths. Because the FSO channel is assumed to be slow fading, the channel state h_i for each wavelength λ_i could be estimated by allocating a small portion of the bandwidth for feedback to determine CSI. In hybrid RF/WDM FSO, the RF is normally chosen for such a purpose. In any given weather, depending upon the channel state, m wavelengths were chosen with greatest channel gains and different transmit power allocated in a way that will maximize channel capacity and consequently improves the system performance. Similar to adaptive transmission is also topology control and load balancing [70].

9.2 Relay-assisted FSO transmission

As the FSO communication is limited to short haul, relaying continues to play a major role to increase reach for meaningful applications [71, 72]. In FSO, the signal transmitted by a source is overheard by other nodes, consequently forming partners, enabling the source and its partners to jointly process and transmit information [73]. All-optical relaying techniques, that is amplify and forward where signal processing is only performed in the optical domain allowing full utilization of optical signal bandwidth, have been considered in these researches. It has also been inferred that this technique is faster, simpler and achieves better results. Decode-and-forward relay-assisted free space optical (DF-FSO) communication systems under atmospheric turbulence-induced fading and misalignment errors was investigated in [74]. Aperture averaging technique was applied at both relay and destination node. Cooperative FSO communication offers combined advantages of wireless optics and cooperative communication, leading to larger bandwidth and hence an improvement in performance [75]. Amplify and forward (AF), DF and two-way relaying [76] are some of the cooperative protocols that have been studied for relay-assisted FSO. However, there has been a proliferation of other strategies such as adaptive detection and forward (ADeF) [77]. In such a scheme, relays would take part in the transmission only if it can receive error-free data from the source. Usefulness of these techniques has been demonstrated in [78]. As an example, the study in [71] considered an FSO span of 5 km in a log-normal channel with

0.43 dB/km weather-induced attenuation. Both serial and parallel relaying using DF and AF with 1 and 2 relays have been analyzed and compared. The results are shown in Table 4. These results give an insight into relay-assisted FSO systems design considerations.

WDM in such FSO relay-assisted systems enables bidirectional communication as well as multiplication of capacity [79], eventually paving way for formation of a full optical multihop broadband access network, especially for future networks that are characterized by increased data rates. The use of FSO in this regard to augment the fiber optic PONs has been explored considering that it is not always feasible to install fiber optic network cables in all places and for all circumstances [80]. Hence, proposals to combine FSO with PONs to form hybrid access networks have been necessitated due to lower costs and higher flexibility. Again, the coverage of a single-hop FSO link is limited to 2 km [80]; therefore, a multihop WDM FSO is a possible solution for extended reach to be effective with flexibility. Such an architecture promises to be a cost-effective all-optical access solution and is shown in Figure 4.

At the Optical Line Terminal (OLT), the optically modulated data from different sources, which might be voice, data, video or images, are combined by a wavelength division multiplexer and transmitted over free space through a number of relays. At each relay node, the composite signal is amplified by an EDFA which should be operated within its gain saturation region. At the remote node (RN), a WDM demux typically separates multiplexed optical signals and route each to different Optical Network Units (ONU) in a point-to-point scheme form over a final FSO hop distribution length. The same arrangement can be used for the upstream transmission to create a full-duplex communication system.

9.3 Hybrid RF-FSO (outdoor)

Several studies have been devoted to solve the instability problem of the FSO link, leading to underperformance or complete outage especially in dense fog, rain or sand conditions [81]. In such cases, the RF link is used as a backup [82]. A routing framework that maximizes the fairness index is required, which is defined as the minimal ratio of data transmitted and data required among all traffic profiles. Joint optimization of simultaneous transmission on RF and FSO channels has been another innovative solution [83]. Furthermore, knowing the outage probability in such hybrid systems can help in power allocation scheme that might lead to outage probability minimization as in [53]. Hybrid RF/WDM FSO links are also being extensively researched currently for wireless mesh networks, to enhance the performance in a similar fashion [84, 85].

9.4 WIFO-hybrid wifi and FSO (Indoor)

WIFO, a hybrid WiFi (indoor) and WDM-FSO for high-speed indoor communication system, is one of the emerging investigation [86, 87]. It is based on the femtocell architecture. This has been motivated by (1) the continued increased in the devices that are connected to the wireless network, putting pressure on the Wi-Fi wireless network which cannot meet the bandwidth demand. (2) Wi-Fi circuitry are not power efficient, in contrast, FSO circuitry and transceivers are known to consume less power. (3) Indoor FSO communication (VLC) increases the capacity with minimum changes to existing wireless technologies. Further, location assisted coding is possible with such systems, resulting in increased throughput. A hybrid FSO/VLC system has been proposed in [88], in which VLC is connected to the FSO backbone rather than the usual power line cables which suffers several impairments leading to high attenuation. Further, diversity techniques have been combined with hybrid modulation schemes such as hybrid pulse position and binary phase shift keying subcarrier modulation (PPM–BPSK–SIM) in [89]. Such an architecture was reported to have a noticeable improvement of 6.5 dB compared to BPSK–SIM alone over a link distance of 1.5 km.

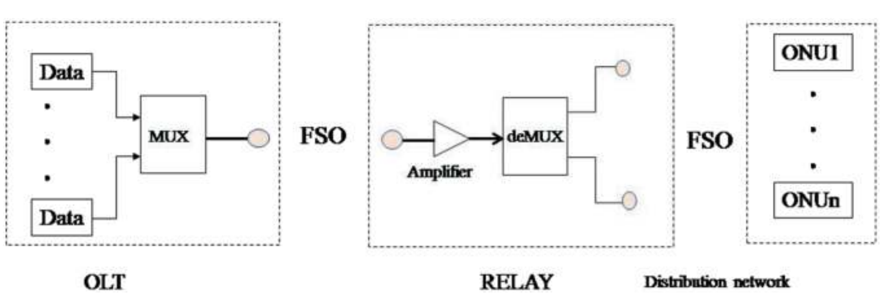

Figure 4: Multihop WDM FSO.

10 Conclusion

WDM FSO technology takes advantages of FSO and WDM such as low cost, increased bandwidth, security, protocol transparent among others. In this article, we have reviewed WDM FSO communication systems as a means of increasing the capacity for increased bandwidth provisioning. Discussed are the channel models and design challenge of WDM FSO for link availability in adverse weather conditions such as haze, rain, fog and heavy fog. Alongside, mitigation techniques have been discussed that include advanced modulation techniques, MIMO concept, adaptive transmission, spectrum slicing and coding. The last section has addressed the current trends as well as some of the emerging areas of interest in WDM FSO. The major focus was on the physical layer.

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