Free Space Optical Communication: A review of Challenges and Mitigation Techniques

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Abstract : Since a last few years, Free Space Optical Communication (FSO) has been used over Radio Frequency technologies for transmission of voice and data. There are many advantages of FSO. It is a technology free of license having an ease of deployment, a high bandwidth and a quite high data rate too. However, it could not attract much attention commercially for it is a technology that is based on light. The performance of a FSOC system is not only affected by atmospheric conditions of haze, fog, rains etc. which can induce fading but also by Angle of Arrival and Pointing error if transmitter and receiver are not aligned precisely. In this paper, we analyze the different challenges faced by FSO system together with the solutions proposed and the way ahead to bring about a further increase in its performance.

IndexTerms **-Free Space Optical Communication, MIMO, OFDM, OSSK, Visible light communication, RF/FSO.**

I. INTRODUCTION

Free Space Optical Communication or wireless optical communication refers to transmission of information making use of optical sources but through an unguided medium which can be free space or atmosphere. Since, it offers a very high bandwidth, it can be used as a solution for congested Radio Frequency spectrum too. FSO transmission works in a similar way as a fiber optic communication system except that here the transmission medium for modulated data is unguided. In an FSO system, if the weather is clear, the transmission can take place in a wavelength ranging from 700nm to 1600nm that is near infrared range. Wavelength for RF based system is a thousand times more than FSO system. Thus, an increase in carrier frequency of FSO also offers an increase the information carrying capacity of the system. Also, since divergence of beam is proportional to wavelength, the spread in beam by an optical carrier is less, so for same power transmitted the signal intensity received is more with FSO than with an RF system. FSO also offers a high directivity and owing to high directivityand low beam spread, it offers a highly secure system. Eavesdropping is not possible as signal cannot penetrate through walls. However, along with advantages come a number of challenges that need to be dealt with to get a high performance in FSO link. Bloom et al. [1] described the FSO link design aspects in detail. The paper deals with various challenges faced in establishing a successful FSO link. Ghassemlouy et al. [2] and Henniger et al. [3] have described various challenges faced in establishing FSO link. their mitigation and the recent work that has been done.

II. CHALLENGES IN FSO LINK DESIGN

FSO link makes use of atmosphere as a channel for propagation which makes it a random system since various random atmospheric phenomenon like clouds, fog, haze, rain etc limit the design and distance of information transmission. Different losses in a terrestrial link include absorption and scattering loss, loss due to beam spread, loss due to atmospheric turbulence, and due to misalignment whereas in a space link, losses are mainly due to atmospheric turbulence, pointing errors and error due to Angle-on-Arrival issue. Below we describe the various losses and their impact on the link.

2.1 Loss due to Scattering and Absorption

A careful choice of wavelength range needs to be done in order to have minimal absorption in FSO system since atmospheric absorption is a phenomenon dependent on wavelength. Water molecules, carbon dioxide and ozone are main absorbers at visible and IR wavelengths [4], [5]. The losses due to these processes have been given by Beer's law [6]. Though there are many transmission windows in 700 to 1600nm range, FSO systems are mainly designed to operate in 780 to 850nm and 1520 to 1600nm range since components of transmitter as well as detector are easily available. In any transmission window, the attenuation due to aerosol absorption or molecular absorption should be less than 0.2dB/Km.
Scattering, too reduces FSO performance. If wavelength is larger than size of particles in atmosphere, then Rayleigh scattering is produced such as in Ultraviolet or visible range else Mie scattering is produced which is in IR range. Fog, Haze and aerosols contribute to Mie scattering. In case of fog which contributes to both absorption and scattering, attenuation is as high as 350dB/km [7], thus requiring a high power laser together with mitigation procedures to ensure that link is available. Impact of rain and snow is not much pronounced as the particles are of larger size than the wavelengths used in FSO links. In order to have maximum link availability, a link margin greater than 30dB is taken to ensure maximum availability of link.

2.2 Loss due to atmospheric turbulence

Due to the variation in temperature and pressure of atmosphere, turbulent cells are formed. These are called eddies. They differ in size and refractive indices thereby acting like a prism which results in interference of beam either constructive or destructive. This leads to energy redistribution. Thus, the intensity and phase of received signal varies due to these random fluctuations. These random fluctuations in intensity are given by scintillation index which is a normalized variance of intensity fluctuations given by [8],[9]. It is a function of refractive index structure parameter which gives the strength of turbulence in atmosphere. For weak turbulence, scintillation index is less than unity whereas for strong turbulence, it is greater than unity. For weak turbulence, intensity statistics are given by log normal distribution whereas for strong, field amplitude has negative exponential statistics given by rayleigh distribution. Infact, gamma gamma distribution is mostly used to describe the scintillation statistics for both weak to strong turbulence.

2.3 Loss due to beam spread

Diffraction near the aperture of receiver results in beam divergence which results in loss of power at the receiver since some fraction of transmitted beam is not collected at the receiver. The loss increases with an increase in the length of link. In order to mitigate it, either the receiver aperture is increased or some diversity technique is incorporated at the receiver end.

2.4. Error due to misalignment

The buildings for FSO mounting might be in continuous motion owing to factors like thermal expansion, high velocity of winds and in case of vibrations. Therefore, transceiver must be aligned accurately by using good tracking as well as pointing mechanisms to prevent link failure.

E. Pointing error

It can arise due to a jitter in platform, vibrations in satellite or due to a stress being developed in any device. It can also happen due to beam wander effect caused by atmospheric turbulence, the beam is thus displaced from its original path which increases the bit error rate of system significantly due to increased power loss [10]-[12]. Since the beam broadens at higher wavelengths, the loss too reduces but the loss is more at visible wavelength. It is mitigated by using adaptive beam control technique. The beam size at the transmitter is adjusted according to system environment.

F. Error due to fluctuation in Angle-of-Arrival

It also happens due to atmospheric turbulence. The image appears to be dancing at the receiver focal plane due to a distorted wavefront arriving at receiver end. This is compensated by using fast beam steering mirrors or employing the use of adaptive optics [13].

III. TECHNIQUES FOR MITIGATION

Propagation through atmospheric channel deteriorates the Bit Error Rate of FSO thereby degrading the quality of the signal at the receiver. In order to enhance the reliability of FSO for any weather condition, several mitigation techniques are employed. For example, multiple beam transmission, relay transmission, hybrid RF/FSO, adaptive optics etc.

3.1 Aperture averaging method

An increase in the receiver aperture averages out fast fluctuations which are caused by small sized eddies thus reducing the channel fading. This parameter which quantifies the fading reduction due to averaging of aperture is called aperture averaging factor, A and is defined as ratio of variance in fluctuations of a signal for a given aperture diameter of receiver to that of a receiver having infinitesimal small aperture diameter. An increase in aperture diameter reduces the atmospheric scintillations thereby improving the BER of the system as given in [14]-[16]. But it also tends to increase the background noise collected by the receiver. Thus, an optimum diameter selection is essential. Gamma-gamma distribution gives the best fit to irradiance statistics for moderate to strong turbulence but if the aperture diameter is large as compared to coherence length of atmosphere, log normal distribution is more appropriate [17].

3.2 Diversity technique

Diversity techniques are employed to mitigate the effects of turbulence in atmosphere. These can be operated on time, frequency or space. An array of receivers with smaller apertures is used instead of using a larger aperture. When this is done, mutually uncorrelated multiple copies of the signal are transmitted in time, frequency or space. This improves both, link availability as well as the BER of the system as in [18]-[19]. It was demonstrated by Gold that using four beams of 514.5nm the value of scintillation index was reduced to 0.045. More the number of beams more is the reduction in index. However, to achieve least correlation between multiple beams, antennas at both transmitter and receiver should be separated by more than atmospheric coherence length as given by [19]-[21]. At the receiver side, we achieve diversity gain by taking average over multiple independent signal paths. Out of the various signal combining techniques at the receiver side, Maximal ratio combining gives better gain but it is complex and costly, so Equal Gain Combining is used. In case of small-scale turbulence, the effect of correlation can be neglected if we employ receiver diversity (SIMO- Single Input Multiple Output) using intensity modulation and direct detection. This has been proved by both wave optics and Monte Carlo simulation [22].

Special space time codes such as the Alamouti code can be used for transmit diversity that is Multiple Input and Single Output. It has been observed that improvement in SNR is directly proportional to the number of transmitter and receiver antennae when Channel State Information is available at the receiver. The outage probability of Gaussian FSO is proportional to square of logarithm of SNR for weak turbulence channel and to logarithm of SNR for moderate to strong turbulence. For an FSO MIMO system, using M-ary PPM together with Multilevel coding and Low Density Parity Check codes has given excellent coding gains for turbulent channel regime [23]-[29].

A form of distributed Spatial Diversity called Cooperative Diversity was employed in [30]. It allows sharing of resources by cooperative communication among multiple terminals. Thus, building of a virtual antenna array in a distributed fashion is possible [31]-[35].

3.3 Adaptive Optics

It is a closed loop control system which mitigates the turbulence in atmosphere by putting the conjugate of atmospheric turbulence. Hence, pre correction of beam distortion is done before transmission in atmosphere. It compensated for the fluctuations in wavefront by transmitting a part of the received signal to wavefront sensor which generates a control signal at the actuators of wavefront corrector. The closed loop frequency for designing AO system should be atleast four times that of Greenwood frequency [36].

3.4 Modulation techniques

The choice of modulation and coding schemes is dependent on two optical power efficiency and bandwidth efficiency. For best results in turbulent atmospheric conditions, OOK requires use of adaptive threshold. It is popular due to its simplicity and is used with IM/DD transmit receive mechanism. Maximum Likelihood sequence detection and maximum likelihood detection can also be used for detection in OOK scheme [37]-[40].

For long distance transmission, M-ary PPM scheme gives a high peak to average power ratio. In it, each symbol is divided into M time slots and an optical pulse is transmitted at these slots while other slots are vacant.

If the system is bandwidth limited, multilevel intensity modulation schemes are used where transmitted data can take multiple amplitude levels as in PAM and QAM [41]-[43]. However, these are not a good choice for a highly turbulent conditions since for achieving a high bandwidth efficiency, power level has to be reduced.For a high background noise, M-ary PPM is considered a suitable choice in which an increase in M further reduces the effect of noise. Different variations of PPM have been proposed in [44] as Differential Amplitude Pulse Position Modulation (DAPPM) and Pulse interval modulation (PIM). Sub-carrier Intensity Modulation with diversity techniques enhances the BER performance. In SIM, the electrical RF sub-carrier is modulated by baseband signal which is further intensity modulated by optical carrier [45]. But it has less power efficiency than OOK and PPM. Differential Phase Shift Keying (DPSK) also received interest due to a 3dB improvement over OOK but its implementation is tough and expensive.

In order to further improve the performance, error control coding is also used such as Reed Solomon code, turbo code, convolutional code, trellis coded modulation (TCM) and LDPC coding which are all forward error control techniques [46]. RS codes provide a good coding gain when they are used with PPM and the improvement increases with increase in length of block. However, for a strong atmospheric turbulence, LDPC, turbo or trellis codes are used. But LDPC are preferred over others for having less complex decoding and reduced computational time. Variable rate LDPC also enhances coding gain and channel capacity over a fixed rate LDPC. For strong turbulence and background noise, LDPC coded MIMO FSO used with M-PPM gives better performance over uncoded system [47]. Orthogonal Frequency Division Multiplexing, if used with suitable error control coding schemes gives good BER performance [48]-[49]. MIMO FSO has been shown to have better performance by using it with Optical Space Shift Keying (OSSK) as it maintains its diversity order even for high turbulence and high Pointing Errors. Also BER performance doesn't vary much from moderate to severe turbulence [58].

3.5 Hybrid RF-FSO

In order to improve the reliability and link availability of FSO, it is teamed up with a more reliable RF system. These are called hybrid RF/FSO which improve the link availability in strong turbulent condition. Even during low cloud conditions, FSO link has a poor availability whereas RF is almost immune to cloud interference. But a continuous switching between RF and FSO can bring the entire system down. So, an alternative approach was proposed in [50] wherein both RF and FSO systems are active simultaneously. It uses a symbol rate adaptive joint coding scheme and also saves the bandwidth. The combination of RF and FSO can solve the issue of capacity scarcity efficiently.

3.6 Hybrid FSO/VLC link

Optical wireless communication in visible spectrum is better known as Visible Light Communication (VLC) system. It uses Light Emitting Diode (LED) based light sources. But they have a limited bandwidth. Hence, a high data rate cannot be achieved even for a small distance. Different modulation schemes were proposed as a solution such as multilevel modulations, OFDM and carrier-less Amplitude and Phase Modulation (m-CAP) [51]. CAP though outperforms OFDM as was demonstrated experimentally. In order to provide last mile and last meter connectivity, first FSO/VLC was demonstrated using OFDM in [52] and using m-CAP in [53]. Here, FSO was used to provide inter building connection and then using Single Mode Fibers, FSO was distributed among different rooms where VLC was used to provide last meter connectivity. Similarly, a hybrid RF-FSO/VLC link was recently proposed and its outage performance was evaluated for different atmospheric conditions. It was found to outperform a single FSO link. Its performance was shown to depend upon available VLC access points. A greater LED output power also improves system performance. Decode and forward relay together with Selection Combining diversity technique was employed.

3.7 Adaptive MIMO-FSO

If the channel state information is made available at the transmitter side also, it is possible to adjust the transmission parameters according to channel conditions. This transmission of feedback information is easier in quasi static channels. In the first proposed adaptive system, the period of adaptive PPM was varied according to channel conditions. In another instance, the code rate was adjusted in OOK in turbo coded FSO.An adaptive modulation scheme was also proposed using M-ary PAM and quasi cyclic LDPC. Either the modulation size or transmission power can be varied to optimize spectral efficiency as well as the average power consumption. Recently an adaptive MIMO-FSO system has been proposed which works in three different modes and the adaptive MIMO is made to select the mode with maximum efficiency and which accomplishes a predefined outage probability target. It employs use of a spatial multiplexing mode, a diversity mode and a hybrid mode which is a combination of two modes.[54]-[57]

IV. Future Scope of FSO

The scope of FSO is quite wide. It can be used to provide internet facility to remote areas. An example is project Loon by Facebook which uses helium balloon in upper layers of stratosphere where the atmospheric turbulences are less but Pointing error and AoA issue needs to be taken care of. Using FSO, satellites themselves can be used for providing internet facility on ground. It can also be used underwater in real time applications to provide a high data rate.

V. CONCLUSION

FSO system, inspite of being vulnerable due to dependence on atmospheric conditions can still provide an ultimate solution for congestion in existing RF spectrum due to tremendous increase in both the number of users as well as the internet services and data services. A number of mitigation procedures have been proposed and to overcome the difficulties in implementation of FSO. The mitigation techniques work almost similarly for both RF as well as FSO system. Work is still being done to optimize the FSO and to make it suitable for last meter connectivity by using it with other techniques like RF and VLC.

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