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A Study on Free Space Optical Communication - Opportunities and Challenges

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ABSTRACT
In today's communication scenario where it has become increasingly important to meet the high data rate requirement, we have to look for alternative ways of communicating rather than depending fully on the prevalent mainstream communication systems. Free space optical (FSO) communication proves to be one of the best candidates to meet these requirements. It resolves the last mile bottleneck connectivity issues especially in local area access networks and acts as an addition to conventional RF/microwave links. This is because of its inherent advantages of license free long range communication, high bandwidth, high data rates, low cost implementation, relatively low power requirement and security compared to existing RF technologies. This paper reviews all the possible opportunities and attached challenges with FSO implementation.

Keywords : FSO, MIMO, Atmospheric Turbulence, Space Time Coding.

I. INTRODUCTION

Free space optical communication (FSO) is a technology in which data is transmitted wirelessly at high rates with the help of optical signals. In contrast to the conventional method of transmitting optical signal through fiber, FSO makes use of free space as the medium to transfer information. It proves to be an excellent candidate for last mile access compared to the traditional last mile delivery systems such as wired LAN, mobile CDN etc. Implementation of a FSO system is quite simple as the working principle resembles that of Infrared TV remote control and wireless keyboard.

Optical wireless communications was first exhibited by an experiment conducted by Alexander Graham Bell in the late nineteenth century. He named it as "photophone", which converted voice sounds into telephone signals and transmitted via wireless medium along a light beam over a distance of around 700 ft. It could not be realized commercially even though his experimentation clearly proved the basic principle of wireless optical communications. Lasers when introduced in 1960s transformed the wireless optical communication scenario. Many military bodies showed their curiosity and enhanced their growth by addressing the principal engineering challenges of FSO. In spite of that the technology failed to meet the requirements when there was a market surge in optical fiber network installation. Early commercial applications of FSO were to provide CCTV video connections and remote LAN-extension services. Over the past two decades, FSO has come up from a niche to deliver mainstream network infrastructure services for free space carrier and telecommunication.

II. WHY FSO?

The last mile bottleneck issue is a major challenge in today's communication era. With the relentless and increasing demand for high bandwidth applications, the last mile access has become a concern. Not only has this been a larger problem, connectivity bottleneck too exists almost everywhere in metro networks. Even though there are several alternatives to address this connectivity bottleneck issue but most of them do not make sense economically. The first and most reliable option is optical fiber communication but the associated cost to lay fiber systems often makes it economically prohibitive. The second option is the radio frequency technology which is a much more mature technology that offers longer ranges but RF based networks require large investments to acquire licensed spectrum. Moreover scaling is a problem with RF networks. The third option is wire and copper based technologies i.e. cable modem, DSL etc. Although copper infrastructure is available almost everywhere and the percentage of buildings connected to copper is much higher than fiber, it is still not an appreciable alternative for solving the connectivity bottleneck as the biggest hurdle is bandwidth scalability. Copper technologies may ease some short-term pain, but the bandwidth limitations of 2 to 3 megabits make them a marginal solution [11].

The most viable alternative is FSO. This technology facilitates an optimal solution, bandwidth scalability, speed of deployment, re-deployment and portability, and cost-effectiveness on an average of one-fifth of the cost required for installing fiber optic system.

III. HOW FSO WORKS?

FSO system consists of optical transceivers with full duplex capability at both ends of a transmission system. It transmits invisible, eye-safe light beams from one transceiver to the other using low power infrared lasers in the terahertz spectrum. The light beams are transmitted by laser light focused on highly sensitive photon detector receivers. These receivers are telescopic lenses that are able to collect the photon stream and reproduce the digital data. Commercially available systems offer capacities in the range of 100 Mbps to 2.5 Gbps, and demonstration systems report data rates as high as 10 Gbps. FSO systems perform communication over distances of several kilometres as long as there is a clear line of sight between the source and the destination with ample transmitter power [11].

IV. ADVANTAGES

Unlike RF and microwave systems, FSO is an optical technology and no spectrum licensing or frequency coordination with other users is required. Interference from or to other systems or equipment is not a concern at all. Electromagnetic interference does not affect FSO link transmission, hence provides immunity to RF interference. The point-to-point laser signal is extremely difficult to intercept, and therefore it is one of the most secured communication. Data rates comparable to optical fibre transmission can be carried by FSO systems with very low error rates. The extremely narrow laser beam widths ensure that there is almost no practical limit to the number of separate FSO links that can be installed in a given location. Since FSO transceivers can transmit and receive through windows, it is possible to mount FSO systems inside buildings, reducing the need to compete for roof space, simplifying wiring and cabling and permitting FSO equipment to operate in a very favourable environment. The most indispensable requirement for optical wireless transmission is line of sight between the two ends of the link. It is undoubtedly a more flexible technology that provides high speed communication. Installation is easy as deployment is quite straight forward and has very low initial investment. FSO facilitates dense spatial reuse. Low power usage per transmitted bit is the advantage of FSO system as it is based on simple on-off keying technique [8].

V. APPLICATIONS

Inter-satellite communication: FSO can be used in deep space for communication between satellites.

Disaster recovery: It works well during disaster situations where mainframe network fails to provide service.

Fibre communication back-up: FSO is used in providing a backup link in case of failure of transmission through optical fiber link.

Storage area network: SAN is built on FSO links to provide access for consolidated block level data storage.

Last-mile access: Laying cables to the end user premises (last mile) is an expensive affair for service providers as the cost of installation in terms of digging to lay fibers etc. FSO can be used to solve such problem.

Enterprise connectivity: The easy installation feature of FSO makes it applicable for interconnecting LAN segments to connect two buildings or enterprise.

Metro-network extensions: It can be used for extending the fiber rings of an existing metropolitan area as FSO system can be deployed in lesser time and connection of new network and core infrastructure is easily done. It can also be used to complete SONET rings.

Links in difficult terrains: It can be used for unapproachable regions and difficult terrains where much intervention is not possible. One time installation of a FSO system in such cases would prove useful.

Mobile wireless backhaul: It can be helpful in carrying the traffic of cellular telephone from antenna towers back to the PSTN with high speed and high data rates.

High-speed low-interference WiFi /802.11 backbones: FSO is beneficial in LAN by supporting high speed data services for mobile users and small satellite terminals. It acts as a backbone for high speed trunking network.

Medical imaging: It can be used in medical domain for viewing the human body to diagnose, monitor or treat medical conditions.

Military access: as it is a secure and undetectable system it can connect large areas safely with minimal planning and deployment time and is hence suitable for military applications.

VI. CHALLENGES

The advantages of FSO do not come so easily without paying anything for it. When light is transmitted through optical fiber, transmission integrity is quite predictable barring some unforeseen events but when light is transmitted through the air it must survive with the complex and not always quantifiable subject – the atmosphere. Few of the factors that greatly affect signal propagation in FSO systems are discussed below:

Atmospheric Attenuation:

Absoption- Absorption is caused due to the presence of water molecules that are suspended in the terrestrial atmosphere. These particles are responsible for absorbing the optical energy as a result of which there is a decrease in the power density of the optical beam. Transmission in a FSO system is directly affected by absorption. Carbon dioxide also causes absorption of the signal.

Scattering- Scattering takes place when the optical beam hits the scatterer. It is a wavelength dependent phenomenon in which energy of the optical beam is not altered. It results in directional redistribution of optical energy which leads to the reduction in beam intensity while transmission over longer distance.

Atmospheric Turbulence:

It is caused due to atmospheric in-homogeneity or random temperature variation along the beam path. The atmosphere behaves like a prism of different sizes and refractive indices leading to phase and irradiance fluctuation. This result in deep signal fades. The size of turbulence cell leads to different types of effects that would be dominant. If size of turbulence cell is of larger diameter than optical beam then beam wander is experienced. Beam wander is defined as the rapid displacement of the optical beam spot. If size of turbulence cell is of smaller diameter than optical beam then the intensity fluctuation or scintillation of the optical beam takes place. Turbulence leads to fading of optical signal power, at times results in complete loss of the signal [10].

Atmospheric Weather Conditions:

Weather conditions are one of the main causes of attenuation in FSO transmission. Some of the weather conditions are discussed below:

Fog: It is one of the major weather conditions that affect FSO propagation. Fog greatly attenuates the visible radiation and has a similar affect on the near-infrared wavelengths employed in FSO systems. The effect of fog on optical wireless radiation is entirely analogous to the attenuation and fades suffered by RF wireless systems due to rainfall. Similar to the case of rain attenuation with RF wireless, fog attenuation is not a show-stopper for FSO because the optical link can be engineered such that, for a large fraction of the time, an acceptable power will be received even in the presence of heavy fog. Optical wireless based communication systems can be enhanced to yield even greater availabilities [9].

Rain: Rain drop sizes are larger than fog and wavelength of light. Extremely heavy rain conditions where one can't see through it results in link failure. Even water sheeting on windows also affects signal propagation. Rain attenuation is because of rainfall which is a non-selective scattering phenomenon. This form of scattering is independent of wavelength. Rain gives rise to fluctuation effects in laser transmission. Visibility of FSO signal relies on the amount of rain. During heavy rain conditions, water droplets are solid compositions that either change the characteristics of optical beam or limits the beam transit as it may undergo absorption, scattering and reflection.

Haze: Haze particles stays for long time in air thereby leading to atmospheric attenuation. As a result, the attenuation value is dependent on the visibility level at a given time.

Smoke: It is produced by the combustion of various substances like carbon, glycerol, and household emission and affects the visibility of transmission medium.

Sandstorms: Sandstorm is a common issue in outdoor communication. This is likely only in desert areas and rare in urban core. Wind particles size that depends on the soil texture and the wind speed needed to blow up the particles during a minimum time period are the major reasons of sandstorms occurrence.

Clouds: Cloud layers are a part of earth's atmosphere. Clouds are formed by the condensation or deposition of water above earth's surface. It can entirely obstruct the portion of optical beam transmitted from earth to space. The attenuation resulting due to clouds is hard to compute because of the diverse and in-homogeneous nature of the cloud particles. Presence of low clouds is same as fog and may accompany rain and snow.

Snow: Snow has larger particles that cause geometric scattering. The snow particles affect in a similar manner as that of Rayleigh scattering. Heavy snow may result in ice build-up on windows and lead to whiteout conditions also.

Pointing Stability – Building Sway, Tower Movement: Only wide beam width fixed pointed FSO systems are able to handle majority of the movement observed in deployments on buildings. Narrow beam systems are unpredictable and seek manual intervention for re-alignment regularly, caused due to building movement. 'Wide beam' corresponds to more than 5milliradians. Narrow systems (1-2mRad) are not dependable without a tracking system.

Effective beam divergence and a suitably matched receive Field-of-View combined together results for an immensely robust fixed pointed FSO system applicable for multiple deployments. Fixed-pointed FSO systems are mostly favoured compared to actively-tracked FSO systems because of less cost.

Scintillation:

Performance of many FSO optical wireless systems is adversely affected by scintillation on bright sunny days; the effects of which are typically reflected in BER statistics. Few FSO products come up with a unique combination of large aperture receiver, widely spaced transmitters, finely tuned receive filtering, and automatic gain control characteristics. Additionally, specific optical wireless systems also incorporate a clock recovery PLL time constant which help in eliminating the atmospheric effects such as scintillation and jitter interference.

Solar Interference:

Solar interference in FSO systems can be tackled in two ways. Optical narrowband filter preceding the receiver detector responsible for filtering all components except the wavelength actually used for intersystem communication. To control off-axis solar energy, sophisticated spatial filters needs to be implemented in Cable Free systems, enabling them to operate without getting affected by solar interference that is greater than 1 degree off-axis.

Physical Obstructions:

FSO products with distantly spaced redundant transmitters and wide receiver optics will be able to eliminate interference from objects such as birds. In a day, an object covering 98% of the receive aperture and all but 1 transmitter; will not cause a FSO link to fail. Hence birds are not likely to affect FSO transmission.

VII. SOLUTIONS TO COMBAT CHALLENGES

Implementation of an adaptive laser power Automatic Transmit Power Control (ATPC) scheme to dynamically control the laser power in response to varied weather conditions will increase FSO reliability. In clear weather conditions the transmit power is significantly reduced, thereby increasing the laser lifetime when laser is operated at very low-stress conditions. In severe weather conditions, the laser power is increased required to maintain the optical link continuity and decreased again as the weather clears. A TEC controller that maintains the laser transmitter diodes temperature in the optimum region maximizes lifetime and reliability with consistent output power making FSO system operates efficiently at higher power levels.

Spatial Diversity (MIMO): Diversity at transmitter and diversity combining at receiver end can successfully combat the degradation caused by atmospheric turbulence in free space optical links. Alamouti space time coding is considered at the transmitter while the receiver employs switch-and-examine combining (SEC) [1]. Numerical results for on-off keying (OOK) modulation are provided and are compared with Monte Carlo simulations. BER expression for FSO link experiencing gamma-gamma fading is derived when Alamouti coding is applied on the transmitter side and switch-and-examine combining is employed on the receiver side.

Suitable STC: A space time code construction with a symbol rate of two for free FSO-MIMO communication systems is proposed [2]. Unlike the radio-frequency space time coding design that deals with complex symbols containing phase and magnitude information, the phase detection in wireless optical communications is very challenging. This restricts optical MIMO codes to carry positive magnitude information belonging to a finite range. To meet these requirements, the authors proposed to design the FSO-MIMO codes considering first the whole real space R, followed by a bipolar to unipolar conversion to fit in the intensity margin. MIMO configurations with two or four transmitters (lasers) are considered. The base is of shape-preserving construction on quadratic extension fields that linearly combine the real symbols to form a full diversity space time code with a symbol rate equal to two. Authors have shown how to optimize the choice of the algebraic field numbers for different configurations to jointly optimize the non-vanishing code determinant and the bipolar to unipolar attenuation factor.

Robust Modulation Techniques: In this paper, authors have designed Q-ary (Q arbitrary) intensity modulation schemes for free-space optical OSTBC communications with arbitrary code dimensions by introducing a modulation mapping function f(•) in the transmitter and a linear post receiving function g(•) in the receiver[3]. Necessary and sufficient condition for the intensity-modulated OSTBC to maintain orthogonality is derived. Finally, the f (•) and g (•) functions that satisfy the necessary and sufficient condition for Q-ary intensity modulation schemes such as PPM, PWM and ASK are formulated. BER performance is verified by simulation in an asynchronous FSO MISO channel setting.

VIII. CONCLUSION

This study depicts the importance of FSO systems and attached challenges.FSO systems transmit data wirelessly using visible to near infrared (NIR) light propagating through the atmosphere as carrier in contrast to optical fiber communication where a dedicated channel exists between transmitter and receiver. It is evident that this form of communication is used in situations where it is impractical to establish physical connections. Signal propagation in FSO is quite challenging and is greatly affected by various atmospheric conditions such as dust, rain, and fog and atmosphere turbulence. These atmospheric attenuation factors are the reason for degradation of FSO link performance. Nevertheless researchers have shown that FSO outperforms conventional RF communication at very high frequencies.

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