An Innovative Methodology of High Performance and Data Security for Free Space Optical Communication

Charu Pandey, Satish Kumar, Rajinder Tiwari
Department of Electronics & Electrical Engineering (ASET),
Amity University Utar Pradesh Lucknow, India
email: charu.pandey15@gmail.com skumar2@lko.amity.edu trajan@rediffmail.com

Abstract- **Free space optical communication involves the use of modulated optical or laser beams to send telecommunication information through the atmosphere. Free-Space Optics (FSO) is a proven, reliable technology for last mile telecommunications applications, used worldwide for both enterprise network building-to-building connections and for wireless access to more traditional land line communications networks. Free Space Optics has become a viable, high-bandwidth wireless alternative to fiber optic cabling. The primary advantages of FSO over fiber are its rapid deployment time and significant cost savings. This paper discusses some of the security features of FSO in detail and describes why FSO is the most secure wireless technology currently available. Given the relative newness of FSO technology in commercial applications, few standardized metrics exist for comparing the performance of different systems. In this paper we also have a goal to explain some of the design issues surrounding FSO systems and to provide sufficient information to allow potential users to evaluate the suitability of a specific FSO system for a particular application.**

Keywords- **Free space optics, laser communication, optical wireless, infrared, atmospheric attenuation, last mile, radio frequency, International Telecommunication Union, fading channels.**

I. INTRODUCTION

Free-space optical communication systems (in space and inside the atmosphere) have developed in response to a growing need for high-speed and tap-proof communication systems. Links involving satellites, deep-space probes, ground stations, unmanned aerial vehicles (UAVs), high altitude platforms (HAPs), aircraft, and other nomadic communication partners are of practical interest. Moreover, all links can be used in both military and civilian contexts. FSO is the next frontier for net-centric connectivity, as bandwidth, spectrum and security issues favor its adoption as an adjunct to radio frequency (RF) communications [1]. While fixed FSO links between buildings have long been established and today form a separate commercial product segment in local and metropolitan area networks [2], the mobile and long-range applications of this technology are aggravated by extreme requirements for pointing and tracking accuracy because of the small optical beam divergences involved. This challenge has to be addressed to fully exploit the benefits of optical links.

1.1 A Typical System of FSOC:

A typical free space optics communication system consists of: a small laser source that can be directly modulated in intensity at fairly high data rates; a beam shaping and transmitting telescope lens to transmit the laser beam through the atmosphere toward a distant point; a receiving lens or telescope to collect and focus the intercepted laser light onto a photo detector; and a receiver amplifier to amplify and condition the received communication signal[3]. The transmitted laser beam passes through the atmosphere and can be absorbed, scattered or displaced, depending on atmospheric conditions and on the wavelength/ line width of the laser source. If the laser beam has to transverse distances shorter than 200-500 m or so, finite movement and sway of the local buildings attached to the system may shift the transmitted beam away from the receiving telescope aperture and outside the angular acceptance angle of the system [4].

Figure 1: Photo of 1.55-μm high power diode laser FSO system

II. FSOC RANGE EQUATION

The FSO range equation combines attenuation and geometrical aspects to calculate the received optical power as a function of range and telescope aperture size. The FSO range equation can be given as:

$$\mathbf{P_R = P_T [\, A_r /(D_1 + R\Delta\theta_1)^2]\, T\, K\, e^{-\alpha R}} \qquad \mathbf{(1)}$$

where P_R is the received optical signal power, P_T is the transmitted optical laser power, A_r is the area of the receiver telescope or collection lens, T is the combined transmission receiver optical efficiency, and the area of the beam at a range R. K is another loss factor that deviates from a normal value of 1 when a non coherent light source, such as an LED, is used. K is equal to 1 for a laser source, and has a value of $A_{det} / A_{LED} < 1$, where A_{det} is the area of the detector and ALED is the area of the LED source [5]. The factor of K takes into account that, because of thermodynamic reciprocity (brightness) considerations, a non coherent optical source cannot be focused to an area smaller than that from which it originated [6]. The FSO range equation can be used to generate FSO SNR or power detection curves as a function of range.

III. BEAM PROPOGATION MODELS (GAUSSIAN BEAMS, 1/E, 1/E², AND FWHA)

Two types of beams are normally used in FSO: the Gaussian beam and the top-hat beam. The typical Gaussian beam is a natural byproduct of the laser resonant cavity. Most lasers produce Gaussian beams that have point-source spatial qualities [7]. For instance, single mode lasers produce the narrowest of Gaussian beams, and the output of the single-mode fiber coupled to such lasers also is Gaussian. For a Gaussian beam, the intensity at a transverse or radial distance (r) from the center of the beam is given below for a beam width, b, at a wavelength l, and beam waist, w_e:

$$\mathbf{J(W/m^2 \simeq J_0/z^2)\exp[-2(\rho/\beta z)2]} \quad (2)$$

$$\mathbf{\beta = (2/\Pi)(\lambda/\omega_e)}$$

The power in the beam radius of r_0 is given

$$\mathbf{P(W) = 1 - \exp[-2(\rho_0/\beta z)^2]} \quad (3)$$

Alternatively, the beam can also be characterized to where its radial amplitude declines to 0.368 (1/*e*) of its peak intensity[8]. A third alternative is to characterize the beam by the full-width at half-amplitude (FWHA), which for the Gaussian beam is 0.589 * b. The gradual falloff of the Gaussian beam inherently results in weaker link performance at the edges of the beam for non tracking FSO systems. An alternative to a Gaussian beam profile is a top-hat beam, which has a virtually uniform power distribution over its entire wave front. The projection of such a beam typically requires a finite source size, which can be accomplished by use of a multimode optical fiber as a power transmit source [9]. A beam of this profile is better characterized by its FWHA (as opposed to its $1/e$ or $1/e^2$ width) inasmuch as the intensity goes through a rapid transition at this diameter and maintains peak intensity over the widest possible angle or divergence [10]. The resulting top-hat beam maximizes the total energy carried by the beam under eye-safe conditions. For most good top-hat designs, the FWHA is ~ 0.9* b, which provides excellent area coverage for platform motion while maximizing the total beam power for the particular eye-safe threshold. The real challenge with the top-hat design is filling the modes of the fiber to produce a beam that is as wide as the fiber's physical core diameter [2].

IV. PERFORMANCE CHARACTERISTICS

4.1 Environmental Factors

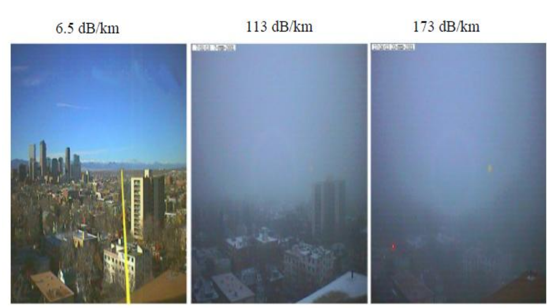
The performance of a FSO link is primarily dependent upon the climatology and the physical characteristics of its installation location. In general, weather and installation characteristics that impair or reduce visibility also effect FSO link performance. A typical FSO system is capable of operating at a range of two to three times that of the naked eye in any particular environmental condition.

4.2 Atmospheric Attenuation

The attenuation of an optical beam as it propagates through the air is given by the Beer-Lambert law as:

$$\mathbf{I(x) = I_0\, e^{-\alpha x}} \quad (4)$$

where Io is the initial optical intensity in watts, I(x) is the intensity after the beam has traveled a distance of x meters, and is the attenuation coefficient of the medium in m-1. Atmospheric attenuation of FSO systems is typically dominated by fog but can also be dependent upon low clouds, rain, snow, dust, and various combinations of each. The effects of fog on visibility and range can be seen in Fig.2 The tall building in the foreground (on the right-hand side) is located approximately 300 m from the camera. The first panel shows clear atmospheric conditions with a visibility range of >2000 m as measured with a nephelometer mounted at the camera site [11]. This corresponds to an attenuation of approximately 6.5 dB/km at near-IR wavelength and according to the 5% contrast standard for visibility and as defined by the World Meteorological Organization (WMO). The distant mountain range is clearly visible, even though it is many kilometers away [12]. The second panel depicts the onset of a fog event, at which time visibility is measured at approximately 113 m (115 dB/km). The near building is still visible at 300 m; all buildings and landmarks beyond this range are obscured. In the third panel, with a visibility range of approximately 75 m (173 dB/km), the building in the foreground is completely obscured [1].



300 m distance to tall building; line is 2.4 km

Figure 2: Fog event

4.3 Alignment:

One of the key challenges with FSO systems is maintaining transceiver alignment. FSO transceivers transmit highly directional and narrow beams of light that must impinge upon the receive aperture of the transceiver at the opposite end of the link. A typical FSO transceiver transmits one or more beams of light, each of which is 5–8 cm in diameter at the transmitter and typically spreads to roughly 1–5 m in diameter at a range of 1 km. Adding to the challenge is the fact that FSO receivers have a limited FOV, which can be thought of as the receiver's "cone of acceptance" and is similar to the cone of light projected by the transmitter.

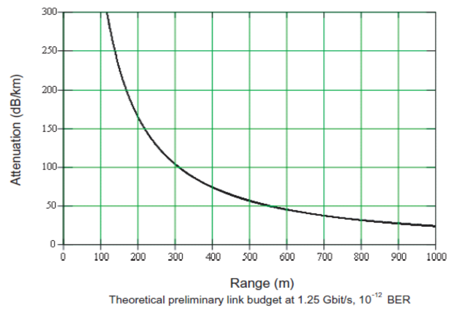


Figure 3: FSO Performance Comparison

4.4 Low-Frequency Base Motion:

Generally, this motion is so insignificant and slow that it goes unnoticed by building occupants [15]. As would be expected, the motion tends to increase with height in a building and can be significant for rooftop installations—even for installations on shorter buildings. Also, it is more pronounced in elevation angles than in azimuth angles [6].

4.5 Moderate-Frequency Base Motion

Moderate-frequency base motion is caused by wind and can be quite significant in tall buildings. FSO outages that result from building motion will be short in duration inasmuch as once the wind gust tapers off, the building will return to its original position and alignment. Wider-beam transceivers and transceivers with sufficiently capable automatic pointing and tracking systems will be able to "reject" even these rare large motions without outage [1].

4.6 High-Frequency Base Motion

High-frequency base motion is caused by vibration. Base motion faster than a few hertz is highly dependent on how and where a FSO terminal is mounted. Fig.4 presents power spectral density plots of vibration for several buildings, mounting hardware must be carefully designed (and installed) so that the mount does not amplify the base motion that the FSO terminal experiences.

4.7 Link Degradation from Base Motion

Base motion can cause link outages in two ways: excess geometric loss due to pointing errors and/or large detector coupling loss due to tracking errors. Geometric loss is the optical loss from the transmit terminal output aperture to the receive terminal input aperture. Detector coupling loss is the ratio of the optical power in the received focal plane to the power incident on the active area of the detector.

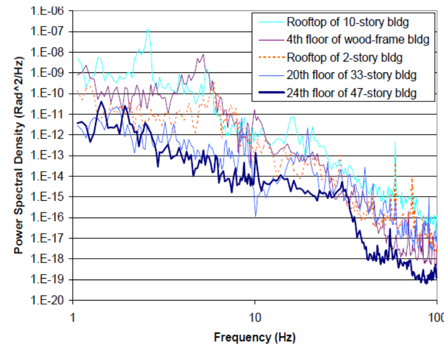


Figure 4: Power Spectral Density of measured vibration

4.8 Solar Interference

A FSO system uses a highly sensitive receiver in combination with a large-aperture lens, and, as a result, natural background light can potentially interfere with FSO signal reception. This is especially the case with the high levels of background radiation associated with intense sunlight [4].

4.9 Atmospheric Effects and Availability

The link equation for a FSO system is actually quite simple at a high level (if we exclude optical efficiencies, detector noises, and so on). The equation is:

$$P_{received} = P_{transmitted} * \frac{d_2^2}{[d_1 + (D * R)]^2} * 10^{(-a * R/10)} \quad (5)$$

Where

P = power,
d_1 = transmit aperture diameter (m),
d_2 = receive aperture diameter (m),
D = beam divergence (mrad) (1/e for Gaussian beams; FWHA for flat top beams),
R = range (km),
a = atmospheric attenuation factor (dB/km).

In above equation, the amount of received power is proportional to the amount of power transmitted and the area of the collection aperture but inversely proportional to the square of the beam divergence and the square of the link range. It is also inversely proportional to the exponential of the product of the atmospheric attenuation coefficient (in units of 1/distance) times the link range.

4.10 Link Budgets

One of the key methods for determining how well a FSO link will perform is to calculate a link budget. Typically, a FSO link budget includes inputs for transmit power, receive sensitivity, optical system losses, geometric losses, and mis-point or alignment loss[8]. Transmit power is the amount of optical energy transmitted by the FSO system; receive sensitivity is the minimum amount of optical energy that must be received by the FSO system for a specified error rate. Optical system losses include scatter, surface reflections, absorption, and overfill losses [9].

Geometric losses are those losses that occur due to the spreading of the transmitted beam between the transmitter and the receiver. For a uniform transmit power distribution with a non obscured transmitter or receiver, geometric losses can be approximated with the following formula:

$$\text{Geometric Loss (db)} = 10\log * \left\{ \frac{\text{Receive Aperture Diameter (m)}}{\text{TX Aperture (m)} + [\text{Range (km)} * \text{Divergence (mrad)}]} \right\}^2 \qquad \textbf{(6)}$$

The basic characteristics of a laser beam provide the following additional advantages of FSO links:

- A narrow beam guarantees high spatial selectivity so there is no interference with other links.
- The high available bit rate allows them to be applied in all types of networks.
- The optical band lies outside the area of telecommunication regulation; therefore no license is needed for operation.
- The small size and small weight of optical terminals enables links to be easily integrated into mobile systems.

V. DATA SECURITY

Two criteria must be satisfied for an individual to overcome the security in a network. If these two primary requirements cannot be met, the security of the network will remain intact. Given these two conditions, will examine how the attributes of FSO transmission can be used to maintain a secure data link:

1) They must intercept enough of the signal to reconstruct data packets.
2) They must be able to decode that information. If these two primary requirements cannot be met, the security of the network will remain intact.

5.1 Preventing Interception of the Signal

Directional transmission: When considering the security of wireless data transmitted through the air, one of the most important elements is the path of the transmitted signal. The directional nature of FSO transmission yields a tremendous security advantage here [9]. FSO uses collimated laser light as the transmission medium; therefore, the signal is kept very narrow throughout its entire path [8].

The absence of side lobes: RF transmission systems are known to "spill" energy in predictable patterns on the sides and to the rear of the antenna [7]. This lost energy is called a 'side lobe' and it typically carries the same signal that is being transmitted to the other end of the link. FSO systems avoid this problem since all of the beam energy is transmitted at a narrow divergence angle [6].

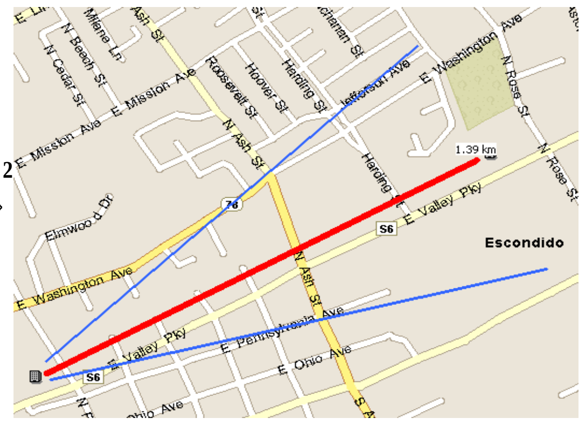


Figure 5: Narrow divergence of the FSO transmit path (shown in red) as compared to a typical Radio Frequency (RF) path (shown in blue). The tightly collimated FSO beam ensures that the signal energy is focused on the receiving unit, making interception of the beam extremely difficult.

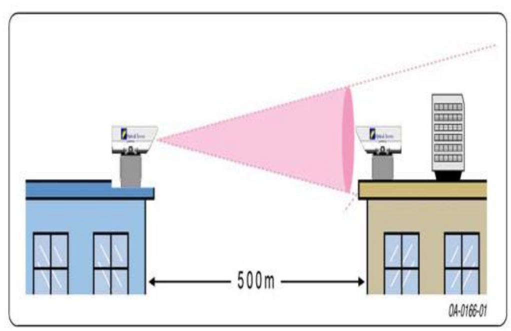


Figure 6: Another view of the narrow beam divergence inherent in FSO transmission. (For clarity only one transit beam is shown.)

The need for a complete, uninterrupted link: FSO terminals require a complete and uninterrupted link for successful operation. If someone attempts to intercept a signal by placing a detector in the path of the beam, the link will be blocked and communication will be terminated.

Therefore, the only way to intercept an FSO transmission is by attempting to "pick off" the narrow beam path from a location behind the building on which the receiving unit is installed. To prevent this highly unlikely event, it is possible to shield the beam so that it does not continue beyond the point of reception.

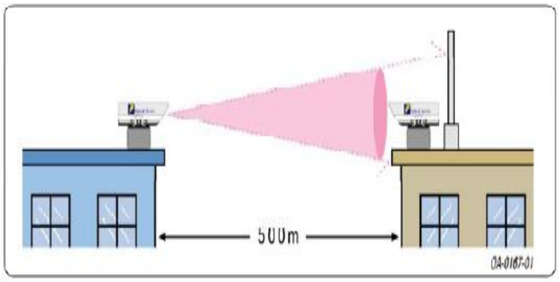


Figure 7: Beam shielded to avoid reception beyond the receiver

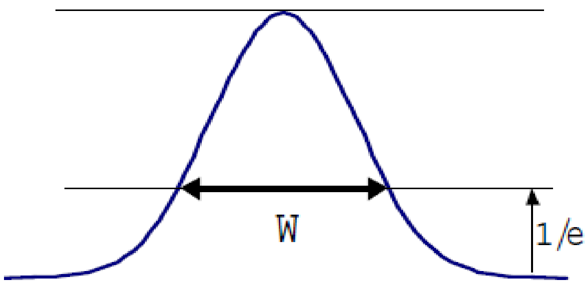


Figure 8: In FSO transmission, the cross-sectional profile of the beam is Gaussian in shape

Chance interception impossible: When light travels through free space, the path can sometimes be altered by heat of other factors. Over a long distance, temperature changes between pockets of air can cause an FSO beam to scatter slightly[9]. This is known as *scintillation*. When the beam is scintillating, photons of light are temporarily steered by pockets of air in random directions. These air pockets are in permanent motion, so the boundaries between the various pockets are constantly changing.. Furthermore, these changes from scintillation last for only fractions of a second. Since the angle of scintillation is random and changes are very fast, it is impossible to forecast a specific spot for intercepting the signal [4].

Misdirection of the beam: It is important to note that if a strong deviation of the beam path occurs unnaturally, the beam will not be received on the opposite side of the link. The networking equipment will automatically halt the transmission until the link is reestablished. Therefore, if someone intentionally aims the system in another direction in an attempt to redirect the signal, the FSO automatically drop the link and stop transmission [6].

5.2 Preventing Decoding of the Signal

With such a "bit in – bits out" design, it might seem as though an FSO signal would be easy to decode. However, because the FSO system can passively transmit protocols, they also retain the security features of those protocols [3]. Therefore, all switching and routing security features existing in a wire-line infrastructure can be carried over to the FSO. Since the FSO systems are also "plug and play", encryption devices can be added to the link to offer additional security. The FSO system can passively re-transmit an encoded bit-stream, making outside signal decoding even more difficult [5].

VI. MERITS OF THE FSOC TECHNIQUE

The basic characteristics of a laser beam provide the following additional advantages of FSO links:

- A narrow beam guarantees high spatial selectivity so there is no interference with other links.
- The high available bit rate allows them to be applied in all types of networks.
- The optical band lies outside the area of telecommunication regulation; therefore no license is needed for operation.
- The small size and small weight of optical terminals enables links to be easily integrated into mobile systems.

CONCLUSION & DISCUSSIONS ABOUT FUTURE WORK

Well-designed FSO systems are capable of delivering 99.9% or better performance at 500–1000-m ranges for the vast majority of cities throughout the world. They are eye-safe and can be used to provision carrier-grade service as long as the appropriate processes have been used to calculate their expected performance. We have attempted to explain how the features inherent to FSO technology make outside interception and decoding practically impossible. Both theoretical and experimental arguments have been presented to demonstrate the security features of the system. This equipment has been used for years by the military in several countries and by other organizations in which secure information is mission-critical. The inherent features of FSO transmission have made it the most secure mode of wireless transmission currently in use.

FSO is just starting to be applied to solve the Internet "last-mile" interconnectivity problem. Some believe that it may be the unlimited bandwidth solution for the metro urban core of downtown building to- building communication, as well as the optimal technology for home-to-home and office-to-office connectivity. FSO systems have been shown to be reliable (99.9% to 99.999%) communication channels with fast bandwidth. They are easy to set up and provide cost-effective solutions. The industry, however, does not yet know how to properly deploy them in telecom networks. To address these concerns, the FSO community recently launched the Free Space Optics Alliance to educate the communication industry as a whole. It is believed that industry-wide education will enable standards to emerge and growth of FSO technology to occur. Finally, it should be noted that to better quantify the technical and scientific aspects of FSO, there is still a need for research in new laser sources, atmospheric spectroscopy, multi beam and active alignment techniques and multi detector averaging.

ACKNOWLEDGEMENT

The authors are thankful to Mr. Aseem Chauhan (Additional President, RBEF and Chancellor AUR, Jaipur), Maj. General K. K. Ohri (AVSM, Retd.) Pro-VC & Director General, Amity University, Uttar Pradesh Lucknow, Prof. S. T. H. Abidi (Director ASET, Lucknow Campus), Brig. U. K. Chopra (Director AIIT & Dy. Director ASET), Prof O. P. Singh (HOD, Electrical & Electronics) and Prof. N. Ram (Dy. Director ASET) for their motivation, kind cooperation, and suggestions.

REFERENCES

[1] D. Sliney and M.Wolbarsht, *Safety with Lasers and Other Optical Sources* (Plenum, New York, 1980).

[2] U.S. Center for Devices and Radiological Health (CDRH), Laser Product Performance Standard, *Code of Federal Regulations,* Vol. 21, Section 1040 (21 CFR 1040) (CDRH, Washington, D.C., 2002).

[3] M. J.Weber, ed., *CRC Handbook of Laser Science and Technology* Vols.1 and 2.

[4] M. J. Weber, ed.*CRC Handbook of Laser Science and Technology, Supplement 1* (CRC Press, Boca Raton, 5) R.Weiner,"Status of laser safety requirements," in *Laser and Optronics 1990 Buying Guide* (1990)

[5] D. C. Winburn, *Practical Laser Safety*, 2nd ed. (Marcel Dekker, New York, 1990).

[6] S. Arnon and N. S. Kopeika, "The performance limitations of free space optical communication satellite networks due to vibrations—analog case," Opt. Eng. **36,** 175–182 ~1997!.

[7] Acampora and S.V.Krishnamurthy, "A broadband wireless access network based on mesh-connected free-space optical links," IEEE Personal Communications, vol. 6, no. 5, pp. 62–65, Oct 1999.

[8] T. ElBatt and H.Izadpanah, "Design aspects of hybrid RF/free space optical wireless networks," in *2001 IEEE Broadband Communications for the Internet Era Symposium digest*, 10-11 Sept 2001, pp. 157 – 161.

[9] X. Zhu and J. Kahn, "Free-space optical communication through atmospheric turbulence channels," *IEEE Transactions on Communications*, vol. 5011) H. Willebrand and B. Ghuman, *Free Space Optics*, 2nd ed. Sams, 2002.

[10] L. W. Couch, *Digital and Analog Communication Systems*, 2nd ed. Englewood Cliffs, N.J.: Prentice-Hall, 2000.

[11] Kim, "Wireless optical transmission of fast ethernet, FDDI, ATM, and ESCON protocol data using the terralink laser communication system," in *Optical Engineering*, SPIE, December 1998, pp. 3143–3155.

[12] M. K. Simon and M. S. Alouini, Digital Communication over Fading Channels. John Wiley & Sons, 2000.

[13] F. C. Leone, L. S. Nelson, and R. B. Nottingham, "The folded normal distribution," Technometrics, vol. 3.

Author's Bibliography

Ms Charu Pandey is presently pursuing M.Tech in Eletronics and Communication Engineering from Amity University, Uttar Pradesh, Lucknow. She has done B.Tech degree course in Electronics & Communication Engineering from Azad Institute of Engineering and Technology, Lucknow in 2011 under the affiliation of the UPTU, Lucknow. Presently, she has focused her working area within the various aspects of the image processing using some suitable simulation software in the vicinity of implementation of some highly efficient and accurate algorithms for digital watermarking. Her research interests also include cooperative communications, free-space optical communications, and optical fiber communications.

Sh. Satish Kumar, M.Tech, FIETE is an alumnus and gold medalist of IIT Roorkee (Erstwhile University of Roorkee). He has worked as General Manager and Chief Vigilance Officer in India's first PSU, ITI Ltd. Bangalore. He has more than 34 years of industrial experience on state-of-the-art telecom equipment and infrastructure dealing with turn-key projects. His professional experience covers the whole spectrum of switching, transmission, access, telemetry and subscriber premises equipment. He also worked for providing design, system integration and Value Engineering solutions for various network based turn-key projects like Army Static Communication Network (ASCON), Integrated Electronic Warfare System (IEWS), Defence Communication Network (DCN), Tactical Communication System (TCS), Network For Spectrum (NFS) etc., Presently he is working as Professor, (Electronics & Communication Engineering) Amity University Lucknow campus.

Mr. Rajinder Tiwari, PhD (P), M.Tech, MIETE is a member of academic staff of Department of Electronics & Electrical Engineering (ASET), Amity University Uttar Pradesh, Lucknow, where he is serving in the capacity of Asstt. Professor in the Department of Electronics Engineering (ASET). He has done M.Tech (I&CE) and M.Sc (Electronics) from NIT, Kurukshetra and University of Jammu, respectively. Presently, he is pursuing Ph.D. (ECE) from Department of Electronics Engineering, Kumaon Engineering College, Dawarahat (Almora) under Uttarakhand Technical University. Mr. Tiwari has given his contribution to the area of Microelectronics (Modeling & Simulation of the Analog CMOS Circuits for ASP Applications), Embedded System Design, Digital System Design and Process Industries Automation and Control System Design (using Graphical Programming Language with dedicated Hardware). He has published several research papers in International/National Journals/Seminar/Conference. He is associated with several technical institutions and bodies as a life member. Before taking the assignment of Amity University, Uttar Pradesh, Lucknow, he had worked in Electronics for Societal Group, CEERI, Pilani, as a Project Scientist and a Multi – National Company as a Sr. Software Engineer (Bridge Instrumentation Division). He is also associated with the successfully implementation of the Hardware and Software for number of projects undertaken by him and in organizing number of International/National Conferences and Seminars.