CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Free Space Optics Communication (FSOC) is a Line-of-Sight (LoS) communication where a modulated optical laser beam (visible/ infrared) is used to transfer high data rates wirelessly through the atmospheric channel (Forin et al 2010; Hu Guo-yong et al 2007). The old Romans and incident Greeks (around 800 BC) used polished metal plates as mirrors to reflect light from one point to another for long range communications (Bell 1880). However, sending information through this transmission method was very limited due to the exchange of predetermined messages only, resulting in low information capacity (Oliver Bouchet et al 2006). In 1792, an optical telegraph based on a chain of semaphores was developed by a French naval navigator called Claude Chappe for communication (Dettmer 2001; Muhammad Ijaz et al 2013a). The US military also used sun-light based power devices to send signals from one mountain top to another mountain top in the early 1800. The blinking of light signals has also been adopted for many years for ship to ship communication (Ronny 2012). During this development period, Alexander Graham Bell constructed a device called ‘photo-phone’ in 1880, which was considered as the rebirth of optical wireless communication. The sunlight modulated by the voice signals using the vibrating mirrors and detected using selenium based photo cell was used. In his experiment, telephone based signals through the atmosphere medium over a range of 200 meters were successfully
transmitted. The restrictions on this work were the crudity of the devices and the intermittent nature of the atmospheric turbidity (Arun K Majumdar & Jennifer C Ricklin 2008).

Experimental exploitation of optical devices for high speed FSOC for long distance requires a monochromatic and narrow strong optical beam at desired wavelength; such a carrier would not have been possible without the invention of Ruby laser in 1960 by Theodore Maiman, which was considered to be the first successful optical laser (Muhammad Ijaz et al 2013a). However, after the invention of the semiconductor optical lasers by Robert Hall in 1962, the FSOC system reliability of operation had increased sufficiently (Goodwin 1970). Today, the semiconductor-injection laser diodes are mostly used for long range optical wireless communication systems (Dale Barry, J 1984; Paul Corrigan et al 2009). After the invention of these sources, the research in FSOC was continued to enhance the system capacity as well as link range and mainly used in military for secure communications in network-centric operational concepts that promote the use of information as fundamental for gaining superiority on the battlefield (Juarez et al 2006). FSOC has also been heavily researched for deep space applications by NASA and ESA with programmes such as the Mars Laser Communication Demonstration (MLCD) and the Semiconductor-laser Inter-satellite Link Experiment (SILE) respectively (Fletcher et al 1991; Toyoshima et al 2001; Yufeng Peng et al 2008). In the past decade, near Earth FSOC was successfully demonstrated in space between satellites at data rates of up to 10 Gbps (Hemmati 2006; Jooshesh et al 2012).

Terrestrial FSOC has now proven to be a viable complementary technology in addressing the contemporary communication challenges, most especially the bandwidth/high data rate requirements of end users at an affordable cost. The fact that FSOC is transparent to traffic type and data protocol makes its integration into the existing access network far more rapid,
reliable and profitable way in comparison to the traditional fibre communications (Ghosh et al 2005). Despite these advantages FSOC performance is degraded by the substantial optical signal losses due to the atmospheric particles absorption and scattering of the propagating optical and infrared waves, since their wavelengths are very close to the wavelengths of these frequencies (Soibel et al 2009). However, in the clear weather condition, theoretical and experimental studies have shown that scintillation can severely degrade the reliability and connectivity of FSOC links (Gappmair and Flohberger 2009; Nistazakis et al 2009). Nevertheless, the atmospheric channel effect poses a great challenge to achieve the link availability and reliability according to the IEEE and ITU link availability standards of 99.999% (five nines) for the last mile access communication network. Therefore, these channel effects at the installation spot still need to be understood and circumvented in order to increase the link range and link availability in terrestrial FSOC systems (Zabidi et al 2010; Wu & Kavehrad 2007; Wakamori et al 2007; Fischer et al 2004).

1.2 RESEARCH MOTIVATION

In the past decade, the world has witnessed a spectacular growth in the traffic carried by the telecommunication networks. As the number of users using applications requiring a large bandwidth is increasingly growing, the bandwidth limits of current wireless systems in radio frequency based technologies are being stretched (Mahdy & Deogun 2004; Muhammad Ijaz et al 2013b). Recently, FSOC systems with a huge unlicensed modulation bandwidth capability have attracted a great deal of interest from a number of sources including academia, industry, telecommunication and standardization bodies (Abdullah Sevincer et al 2010). This huge bandwidth represents high potentials in terms of capacity and flexibility thus making FSOC technology particularly an attractive candidate for multi-gigabit wireless applications including audio, video streaming, multi-gigabit file transferring and internet
revolution for last mile access network, mobile telephony backhaul (3G), satellite communication offering better quality and user experience, in areas to complement radio frequency RF based services (Oliver Bouchet et al 2006; Cvijetic et al 2009; Kaushik et al 2012).

FSOC is getting increased popularity during last few years due to its increased power efficiency for reasonably longer distances. Moreover, it provides data rates that can cater for our future broadband telecommunication requirements besides resolving the last mile access bottleneck. FSOC technology has attractive characteristics like dense spatial reuse due to light beam directionality (Pederson, D and Solgaard, O 2000), low power usage per bit, and licence-free band of operation etc (Arun K Majumdar & Jennifer C Ricklin 2008). Since more than a decade an increasing demand for high bandwidth transmission capabilities can be noted, which should be flexible, allow quick and easy installation at low costs. Among other technologies, this has attracted much attention for wireless optical point-to-point transmission (Phillip sprangle et al 2009). This trend is supported by the development of several new opto-electronic components and the increase of data rates in wide area fiber optic networks, which outperform any other transmission technology today in typical ambient conditions (Hamid Hemmanti 2009).

Figure 1.1 A typical concept of FSOC network
FSOC network for ground-to-ground, ground-to-space, space-to-space and space-to-ground data link is shown in Figure 1.1. These links may include, for example, a metropolitan network between office buildings, a long-distance wide network between ground stations and satellite platform, or an inter-satellite link (Scott Bloom et al 2003). Another area of interest is the broadband wireless solution for closing the so-called last mile connectivity gap throughout metropolitan networks. Different network architectures and the usage of optical repeaters, point-to-point, and point-to-multipoint solutions are also possible in FSOC with the presently available opto-electronic components (Pham Tien Dat et al 2011; Yu-Tai et al 2005).

Recent rapid progress in information and communication technologies has exceeded our expectations for meeting the requirements of multimedia society in the 21st century. FSOC is considered to be one of the key technologies for realizing very-high-speed full duplex multi-gigabits-per-second (multi-Gb/s) large-capacity throughput aerospace communications for voice, video and data information (Ciaramella et al 2009; Tadao Nagatsuma, 2014). Using lasers as signal carriers, FSOC can provide a LoS, wireless high-bandwidth communication link between remote sites. Rapidly growing use of the Internet and multimedia services (Kenneth J Grant et al 2006a) has created congestion in the telecommunications networks and placed many new requirements on carriers. Laser transmitters offer an intermediate low-risk means to introduce desired network functionalities with extremely high bandwidth (Muhammad Saleem Awan et al 2009). The wireless aspect of FSOC can be a crucial advantage, particularly in Local Area Networks (LANs) and Metropolitan Area Networks (MANs) where in cities the laying of fiber optic cables is expensive/ difficult.
FSOC offers substantial advantages over conventional RF wireless communications technology, including higher data rates, low probability of intercept, low power requirements, and much smaller packaging (Arnold Tunick 2007a). FSOC systems have proved to be a viable alternative to optical fiber based systems in several applications, as the technology comes closer and closer to providing the 99.999% service that many corporations require of their data networks. During the last thirty years, great advances have been made in electro-optics and opto-electronics and incorporated into today's FSOC systems, mostly for defence applications (Peng Liu Kazaura et al 2010). Furthermore, given the fact that the optical spectrum is unlicensed with frequencies of the order of hundreds of terahertz, FSOC can be installed licence-free worldwide. Most FSOC systems use simple ON-OFF keying as a modulation format, like the same standard modulation technique that is used in digital fiber optics systems. This simple modulation scheme enables FSOC systems to provide bandwidth and protocol transparent physical layer connections. The other proposed methods to tackle the “last mile” bottleneck are Power-Line Communication (PLC), Digital Subscriber Loop (DSL) or cable modems, Fibre To The Home (FTTH), Local Multipoint Distribution Service (LMDS), and Ultra-Wide Band (UWB) technologies. The limitations and demerits of these methods are (i) more expensive (ii) easily damageable (iii) timeconsuming (iv) complication to maintain and reconfiguration (v) dependency of the common radio link (vi) attenuation and outage during rainfall (vii) carrier frequency licence band issue and (viii) frequency interference with other system, etc (Muhammad Ijaz et al 2013a).

FSOC, a fibreless, laser driven technology offers similar capacity to that of optical fibre based communication with significant reduction in cost and time. The integration of FSOC into the access network can be done relatively cheaply and quickly as it is transparent to the traffic type and protocols. However, the channel in FSOC poses a great challenge and the
performance of FSOC system is subject to abrupt changes in atmosphere. Therefore, it is desirable to experimentally characterize and analyze the system performance under the different atmospheric conditions. A number of authors have studied the effect of atmospheric turbulence, however, most of the studies are theoretical, analytical, simulation or indoor laboratory based setups and very little work has been reported with real outdoor experiment (Jing Li (Tiffany) and Murat Uysal 2003). This is because in practice, it is very challenging to measure the effect of the atmospheric turbulence under diverse conditions (Mzee S Mndewa et al 2008). This is mainly due to the long waiting time to observe and experience reoccurrence of different atmospheric events (Muhammad Ijaz 2013a). However, when the link length exceeds several hundred meters, irradiance fluctuations of the received optical signal due to the turbulence pose a severe problem (Naresh Chand 2000).

The turbulence induced by the random fluctuation of temperature and pressure results in random variation of the atmospheric refractive index. The variations in the refractive index along the optical path cause random fluctuations to the received optical irradiance, which can lead to severe system performance degradation (Tom Garlington and Maj Joel Babbitt 2005). Very little work on the Bit Error Rate (BER) performance of an FSOC link in real outdoor link over the longer period is reported. Therefore, this research work characterizes the atmospheric turbulent channel in different weather conditions together with the profile of data carrying optical beam (Zhang Qingfang et al 2011). The dependence of the atmospheric channel effects and mitigation technique are considered to be an important parameter in order to achieve maximum transmission span. Despite the advantages of FSO links operating them at THz and FIR, wavelength bands would require highcost components that are not readily available at the moment. Therefore, almost all commercially available FSO systems operate in the wavelength range of 0.60 µm – 1.55 µm.
1.3 CHARACTERISTICS OF FSOC

The main characteristic properties of the FSOC are as follows:

1.3.1 Directionality of the Light Beam

The light beams used for FSOC are much narrower and typically have an angular width of 1 mrad, as opposed to omni-directional RF, which occupies $360^\circ$ in a plane. Because of this, there are generally no interference issues in FSOC and there are no or very little medium access issues (Mazin Ali A Ali 2013a). Directionality also helps in localization, because it is very easy to get orientation information of the neighbour, unlike wireless RF network.

1.3.2 Form Factors, i.e., Size and Power Per Bit

The size of the equipment used for short range FSOC can be small i.e., a few centimeters. Semiconductor lasers and LEDs used for FSOC are of very little power (a few milliwatts) that makes it suitable for power limited ad-hoc, sensor network and multi-hop network scenarios to improve the link quality and reduce the Peak to Average Power Ratio (PAPR) (Arun K Majumdar & Jennifer C Ricklin 2008).

1.3.3 Ability to be Operated Licence-free Worldwide and Quick Installation

Optical wavelengths are licence free and FSOC deployment does not require any permission as long as they are safe to the eye. The FSOC systems can be deployed in an ad-hoc manner and typically can be installed in a single day (Narottam Das 2012). Also, the system can be made to operate behind transparent windows, avoiding expensive rooftop rights.
1.3.4 Wavelength Selection Criteria

The choice of the transmitting laser wavelength will depend upon the atmospheric propagation characteristics, optical background noise, and the technologies developed for lasers, detectors, and spectral filters. For a long atmospheric channel, the wavelength will generally need to be restricted to spectral regions of very low atmospheric absorption. Another consideration is intensity fluctuation (scintillation) due to turbulence. The strength of intensity fluctuations decreases as $\lambda^{-7/6}$: thus, scintillation and hence BER can be decreased by using a longer wavelength (Hamid Hemmati 2009).

![Figure 1.2 Contribution of Rayleigh scattering, Mie scattering and water vapor to the atmospheric transmittance.](image)

Figure 1.2 shows the variation of transmittance of the atmosphere resulting from molecular scattering, water vapour absorption and aerosol scattering by various components ($O_2$, $H_2O$, $CO_2$, $O_3$) according to wavelength in the 400 to 2600 nm range. Notice that the band structure is mainly due to water vapour. Effects of molecular scattering are not noticeable over 1000 nm while aerosol scattering is noticeable all over the spectrum (Hamid Hemmati 2009).
1.3.5 Challenges and Limitations

In order to ensure the quality and reliability of data link access through FSOC technology, an accurate characterization of data transmission for different environmental conditions is of utmost importance (Awan et al 2009a). In case of strong atmospheric turbulence, the optical beam undergoes serious challenges in terrestrial FSOC systems and the data rate it could operate is degraded. The major challenges are (i) Real-time study on atmospheric turbulence strength at the location where the system is installed (ii) Beam stabilization on the detector plane and (iii) wavefront distortion equalization (Nester O Perez-Arancibia et al 2012; Plett et al 1999).

1.4 APPLICATIONS & ADVANTAGES

Some of the typical scenarios where the FSOC could be employed are given as follows:

- LAN to LAN connections on campuses/in city at Fast-Ethernet or Gigabit-Ethernet Speeds.
- Speedy service delivery of high-bandwidth access to fiber networks.
- Temporary network installation (for special events or other purposes).
- Re-establishing high-speed connection quickly (Disaster Recovery and Emergency Response).
- Communications between ground and spacecraft, or between spacecrafts, including elements of a satellite constellation.
- Interstellar communication.
• Ship-to-ship communications with high data rates providing complete security

• Military / Defence communications.

Some typical advantages possible with FSOC are:

• High data rates.

• High transmission security.

• No Federal Communications Commission (FCC) licence or frequency allocation.

• Light weight, small volume, and lower power consumption, providing a potential edge over RF communication.

• Portability and quick deployment

• Increased security due to the laser's narrow beam-ideal for the wireless transfer of financial, legal, military / Defence and other sensitive (highly secured) information.

1.5 RESEARCH OBJECTIVES

The prime aim of this research work is as follows:

(i) To develop a model that relates the received optical signal fluctuation with the atmospheric turbulence changes based on the experimental data for modeling and simulation of atmospheric characteristics.

(ii) To develop and demonstrate mono-pulse, Artificial Neural Network (ANN) and parallel processor based steering technique in Terrestrial Free Space Line of Sight Optical Communication (TFSLSOC) on a testbed with a simplex communication link for a range of 500m.
1.6 ORIGINAL CONTRIBUTIONS - NEWNESS AND ACHIEVEMENTS

As a direct result of this research, the following original contributions have been made:

(i) The experimental setup, wireless optical transmitter and receiver system with desired opto-electronic devices has been erected for 0.5Km link range at an altitude of 15.25m through which the entire research work is carried out.

(ii) A new lowcost dynamic measurement system is developed with high accuracy of correlation coefficients of 99.92, 99.63, 99.73 and 99.88% for windspeed, temperature, relative humidity and pressure respectively, used to continuously acquire the meteorological data which are the only input to develop model and characterize the turbulence channel.

(iii) Separate models are developed for predicting the atmospheric attenuation and turbulence strength as a function of local meteorological data acquired in various outdoor environmental conditions (since the optical wave propagation in the atmosphere is season dependent) and prediction accuracy of 0.041dB/km for atmospheric attenuation and 0.000631x10^{-9} m^{-2/3} for turbulence strength are achieved and validated against the selected existing models.

(iv) The optical beam fluctuation due to atmospheric turbulence and the dynamic disturbance is mitigated by using two different controllers (developed based on Response Surface Model (RSM) and ANN) and implemented in MATLAB environment at the receiver station. The performance of the developed controllers is intensively tested in real time and an outstanding behaviour from neural-controller is achieved.
A pipelined-parallel digital architecture is developed in Field Programmable Gate Array (FPGA) according to the proposed software neural-controller structure and the timing performance in terms of correction speed and accuracy is significantly improved.

The quantitative analysis of FSOC data transmission quality and reliability metrics are measured with and without beam Pointing, Acquisition and Tracking (PAT) system through which the maximum possible data rate the system could operate is characterized.

1.7 ORGANIZATION OF THESIS

The thesis has been organized in seven chapters as follows:

Chapter One - Introduction: A complete foreword of the FSOC technology, research motivation, characteristics, typical applications and advantages are presented together with their distinctive features. It also consists of objectives of the research as well the original contributions.

Chapter Two - Real-Time Measurement of Meteorological Parameters for Estimating Low-Altitude Atmospheric Turbulence Strength ($C_n^2$): A complete overview of meteorological parameter influence on the propagating laser beam and the state-of-art literature review are presented. The detailed description on the configuration of field test experimental setup is introduced and the measurement technique is outlined. The specialized weather sensors interfacing technique, simulation results and data conversion methods are described. The performance calibration of the proposed measuring instrument is detailed along with uncertainty computation results. A more common method of atmospheric turbulence strength estimation (Arnold Tunick et al 2005b; Eun Oh et al 2004; Steve
Doss-Hammel et al 2004; Arun K Majmudar & Jennifer C Ricklin 2008) is reviewed and the final formula is interpreted. The measurement and estimation results acquired in different seasons for the diurnal period are discussed along with the associated meteorological parameter variation data.

**Chapter Three - Comparison of different models for ground-level atmospheric attenuation and turbulence strength (Cn²) prediction with new models according to local weather data for FSO applications:**
The main objective of this chapter is developing separate models to have more accurate estimation on atmospheric attenuation (Aatt) and turbulence strength (Cn²). Background and related works are reviewed and the results are presented. Experimental setups and instrumentation assembly on the vibration damped optical bread board are described. Various existing models developed based on the theoretical, analytical, empirical and experimental approach to estimate the Aatt and Cn² are reviewed. The development of new models based on the ANAlysis Of Variables (ANOVA) method as a function of local meteorological data, fitting different local outdoor environmental conditions is described. The comprehensive analyses carried out on the measurement and estimation values associated with different weather seasons, the results in terms of estimation accuracy, Root Mean Square Error (RMSE), are discussed. It also highlights the estimation ability of the new proposed models.

**Chapter Four - Mitigation of Beam Wandering due to Atmospheric Turbulence and Prediction of Control Quality using Intelligent Decision Making Tools:** This chapter outlines various atmospheric effects on the propagating optical beam and the method of stabilizing the center of the beam at the detector plane. Results of the state-of-art literature review are presented. The opto-electronic assembly and setup of FSO link (unmodulated beam) established are described and the inherent
linear/non-linear behaviour of individual parts is highlighted. The design approach of Response Surface Model (RSM) and neural controller model are described. The experimental confirmatory test results associated with the control ability of these controllers in terms of time and accuracy are discussed and the improved performance of FSOC link reliability is analyzed.

Chapter Five - Low Power and Compact RSM and Neural Controller Design for Beam Wandering Mitigation with a Horizontal-Path Propagating Gaussian-Beam Wave: Focused Beam Case: This chapter introduces the necessity for hardware realization of the proposed controllers. The background and related works are presented. The experimental plant configuration layout with aerial view and data handling and manipulation hardware design flow are explained. The design and implementation of the proposed controllers in FPGA are described. The hardware controller performance in beam centroid stabilization in open and closed loop configuration using the developed test bed is intensively tested and associated results are analyzed.

Chapter Six – Quality Metrics and Reliability Analysis of Terrestrial Free Space Optical Communication in Different Open-Atmospheric Turbulence Conditions together with Beam Wandering Compensation: In this chapter, the parameters corresponding to the analysis of quality and reliability of the FSOC data transmission are introduced. The overviews of literature survey results are presented. Further, it relates the atmospheric attenuation, turbulence strength and scintillation index estimated using new proposed models with the data transmission, direct detection and measurement of quality and reliability of FSOC system. These estimation and measurement results corresponding to different weather data are explained. The experimental results and characterization of maximum data rate that the system could operate in various outdoor weather conditions with & without PAT are presented in detail.
Chapter Seven – Conclusion and Future Work: Summary of newness and findings are presented in this chapter. The conclusion as well as the future work are outlined.

The overall contribution of the thesis is schematically illustrated using a research road map as depicted in Figure 1.3.

Figure 1.3 Outline of the research road map and original contribution