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On Prototyping Multi-Transceiver Free-Space-Optical Communication Structures

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Abstract

Wireless networking has conventionally been realized via radio frequency (RF) based communication technologies. However, the capacity of these networks are limited by the availability of the RF spectrum. Free-Space-Optical (FSO) communication has the potential to deliver wireless communication links at optical-level speeds. Although it has the advantage of the high speed modulation, maintenance of line-of-sight (LOS) between transceivers during an ongoing transmission is an important issue since FSO transmitters are highly directional. In this thesis we present a prototype implementation of such *multi-transceiver electronically-steered* communication structures. Our prototype uses a simple LOS detection and establishment protocol and assigns logical data streams to appropriate physical links. We show that by using multiple directional transceivers we can maintain optical wireless links with minimal disruptions that are caused by relative mobility of communicating nodes.

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Chapter 1

Introduction

Optical communication is any form of telecommunication that uses light as a transmission medium. An optical communication system consists of (i) a transmitter, which encodes a message into an optical signal, (ii) a channel, which carries the signal to its destination, and (iii) a receiver, which encodes the message from the received optical signal. The technology has been used for centuries; many techniques such as ship flags, smoke signals, and beacon fires are the earliest form of optical communication. Optical communication has become more and more interesting over as an adjunct or alternative to the radio frequency communication over the last two decades.

The most recent form of optical communication employs a modulated light source that transmits an optical signal, and a photo-detector which reproduces the received optical signal and converts to an electrical signal. Fiber-optic communication uses optical fiber to transmit the light along its path. Optical fibers can carry light signals accross greater distances with less loss than metal wires and are immune to electromagnetic interference. Fiber optic communication systems are widely used in the telecommunications industry and have largely replaced copper wire communications due to their many advantages over electrical transmission. Optical fiber has significantly lower attenuation and interference compared to existing copper wire in long-distance high-speed applications. As a wireless communication technology optical wireless (OW) is a promising approach that can complement the rapid growth of wireless network devices. OW provides freedom from fading and a large bandwidth which can reflect on the achievable data rate.

Another name for OW is Free Space Optics (FSO) which simply means that the communication technology uses light propagating in free space to transmit data between two points. The technology is useful where the physical connections by the means of fiber optic cables are impractical due to high costs or other considerations. Free-space-optical links can be implemented using infrared laser light, although low-data-rate communication over short distances is possible using LEDs. Infrared wireless (IR) is very simple form of free-space-optical communications. Maximum range for terrestrial links is in the order of 2 to 3 km, but the stability and quality of the link is highly dependent on atmospheric factors such as rain, fog, dust and heat. In outer space, the communication range of free-space-optical communication is currently in the order of several thousand kilometers, but has the potential to bridge interplanetary distances of millions of kilometers, using optical telescopes as beam expanders.

Free-space-optical transceivers are cheap (less than $1 per transceiver package), small ($\sim 1mm^2$), low weight (less than 1g), amenable to dense integration (1000+ transceivers possible in 1 sq ft), very long lived/reliable (10 years lifetime), consume low power (100 microwatts for 10-100 Mbps), can be modulated at high speeds (1 GHz for LEDs/VCSELs and higher for lasers), offer highly directional beams for spatial reuse/security (1-10 microrad beam spread), and operate in large swathes of unlicensed spectrum amenable to wavelength-division multiplexing (infrared/visible).

Besides these advantages, FSO requires clear line-of-sight (LOS), and LOS alignment between the transmitter and receiver for communication. Maintenance of line-of-sight (LOS) between transceivers during an on-going transmission is an important issue since FSO transmitters are highly directional.

The bandwidth capacity gap between RF (Radio Frequency) wireless and optical fiber (wired) network speeds is huge because of the limited availability of the RF spectrum [16]. In order to bridge this capacity gap, high-speed point-to-point free-space-optical (FSO) communication has received attention particularly for high-altitudes, e.g., space communications [15], and building-top metro-area communications [5, 6]. Various techniques have been developed for such fixed deployments of FSO to tolerate small vibrations [50, 51], swaying of the buildings, using mechanical auto-tracking [23, 35, 40] or beam steering. But none of these techniques target mobility. Main focus of these efforts has been on reaching *long* (i.e., ∼kms) communication distances with *highly expensive* FSO components (e.g., lasers) with sensitive mechanical steering technologies. FSO provides angular diversity and spatial reuse, which makes FSO even more attractive when combined with its optical transmission speed. However, FSO requires clear line-of-sight; contrary to RF, beam propagation is not omni-directional, which creates a challenge for mobile FSO deployments.

Mobile communication using FSO was considered for indoor environments, within a single room, using diffuse optics technology [19,21,34]. Due to limited power of a single source that is being diffused to spread the optical beam in all directions, diffuse optics can reach typically tens of meters and are not suitable for longer distances. Similarly, for optical interconnects, auto-alignment or wavelength diversity techniques improve the misalignment tolerances in 2-dimensional arrays [20,22,27,28,39]. These

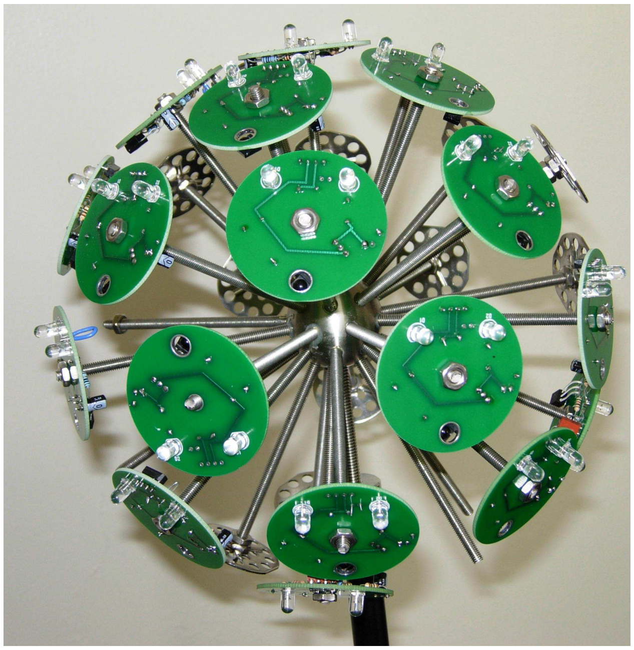

Figure 1.1: 3-D optical antenna design.

techniques involve cumbersome heavy mechanical tracking instruments. Moreover, they are designed to improve the tolerance to movement and vibration but not to handle mobility. Thus, mobile FSO communication has not been realized, particularly for ad hoc networking and communication environments.

Recent research has shown that FSO mobile ad-hoc networks (FSO-MANETs) can be possible by means of "optical antennas" [43,62], i.e., FSO spherical structures covered with optoelectronic transceivers each of which is pointing to a different direction. Such FSO spherical structures achieve *angular diversity* via spherical surface, *spatial reuse* via directionality of FSO signals, and are *multi-element* since they are covered with multiple transceivers (e.g., LED and photo-detector pair). In this thesis we present a proof-of-concept prototype of such a spherical FSO structure (like the one shown in Figure 1.1) with multiple transceivers and its performance. Unlike the traditional mechanical steering mechanisms for LOS management, we use a simple handshaking protocol to “electronically steer” the LOS alignment onto the correct transceiver. We provide proof-of-concept experiment results showing feasibility of achieving optical wireless link over such multi-transceiver structures. The design of the prototype consists of 3 FSO transceivers connected to a circuit board with a microcontroller and microcontroller connects to a laptop computer through RS-232 serial port.

The goal of this initial design is to show the “electronic steering” mechanism and maintenance of line-of-sight (LOS) between transceivers during an on-going transmission. The prototype uses an LOS detection and establishment protocol and assigns logical data streams to the appropriate transceivers when the nodes are mobile. We show that by using multiple directional transceivers our prototype can maintain optical wireless links with little disruptions that are caused by relative mobility of communicating nodes. We present 6 experiments in which we test the feasibility of LOS alignment protocol and the performance of our prototype.

This thesis is organized as follows: Chapter 2 provides a summary of relevant research efforts in the literature, their common use cases, problems and solutions in those fields. Chapter 3 gives the details of our prototype with a basic explanation of related technology and LOS alignment protocol. Chapter 4 summarizes our research by discussing results of experiments that we conducted with our prototype. In Chapter 5, we lay out unresolved problems that can potentially increase the system throughput.

Chapter 2

Literature Survey

This chapter summarizes the literature background of our work with Free-Space-Optical MANETs. We cover several papers to serve the purpose, starting with a general introduction on bandwidth expectations of future applications. FSO-MANETs related work in the literature can be categorized into five main groups:

- high-speed FSO communications,
- terrestrial last mile and indoor applications
- mobile FSO communications,
- effects of directional communication on higher layers, and
- effects of atmospheric conditions on FSO

2.1 High-Speed FSO Communications

Multimedia applications with their unique traffic characteristics and service requirements have an interesting challenge in the Internet today, where the demand for high-speed communication seems to always exist with more bandwidth requirements. Internet Service Providers (ISPs) are laying fiber and will continue to do so gradually (not aggressively though) since the fiber is economically the most viable solution when evaluated based on the gained bandwidth against copper-based technologies. As a reason of growing global bandwidth demand, ISPs have drastically increased their long-haul fiber network bandwidth capacities but wired optical coverage is still not able to reach as many places as the basic telephone service, because the initial cost to lay fiber optical cable is widely considered as *sunk cost*. Reliable sources [9] report today that only 15% of the commercial buildings in major metropolitan cities are connected to a fiber network.

Optical communication has been used for more than 3 decades in various forms to serve fast communications links in remote locations. As a wired technology fiberoptic communication have worldwide acceptance and it is the most capable of high speed data tranmission. However, FSO communication is still considered new and using similar optical transmitters and receivers it can reach as similar data transmission capabilities as optical fiber communication using WDM-like technologies [18]. Today, the most common type of optical communication systems are using optical fibers and can reach even beyond 1 Terabit/s capacity and deployment of free space optical communications is still its infancy although it has several positive features such that it can provide fexible, easy-to-install and practical links.

The authors of [18] review a novel FSO system that represents a breakthrough in the area of FSO communications. They propose a hybrid system that encompasses a pair of novel terminals which allows direct and transparent optical connection to common single mode fibers and include dedicated electronic control unit that effectively tracks the signal beam wandering due to atmospheric turbulence and mechanical vibrations. The system is a 1.28 Terabit/s (32x40 Gbit/s) WDM transmission system. The technical details and experimental results (BER, performance, reliability and eye diagram) of this system show that FSO has significant potential for higher capacity and reliability which can make it a reliable technology for a much wider range of outdoor applications.

This section provided an idea on the efforts of laying fiber in the last decade and their relatively success compared to copper-based technologies. These efforts stand for themselves as an evidence for the requirement of high-speed demand, even 10 years ago, and the harshness of initial sunk costs which shows that FSO can be used to remedy this problem.

2.2 Terrestrial Last Mile and Indoor Applications

Free-Space-Optical (FSO) technology can be successfully used in various applications which include space communications (e.g., inter-satellite and deep space) [13] and terrestrial communications (e.g., enterprise connectivity, last mile access network and backup links).

A summary of ten years history is given in [13] about developments, ranging from different optoelectronic parts and front-end electronics to different in-orbit demonstrations. The authors propose that the use of off-the-shelf devices require extensive analysis in order to be fully applicable in the aforementioned fields of optical wireless technology and major breakthroughs for the implementation of optical wireless links in space will not be possible until dedicated circuits such as mixed analog-digital ACICs are developed. On the other hand, optical wireless is a promosing approach for space communication since reducing the mass of the aircraft is a big advantage which decreases fuel requirements and replacement for new payloads. The authors report that the harness in the aircraft consists of 10% of the dry mass and more than one half of this mass is data wires.

Free-space-optical (FSO) wireless, communication technologies use high-powered lasers and expensive components to reach long distances. Thus, the main focus of the research has been on offering only a single primary beam (and some backup beams); or use expensive multi-laser systems to offer redundancy and some limited spatial reuse of the optical spectrum [23,59]. Main target application of these FSO technologies has been to serve commercial point-to-point links which can operate 155 Mbps to 1.25 Gbps, from 300 meters to 4 kilometers (e.g., [3,5,6])in terrestrial last mile applications and in infrared indoor LANs [21,34,48,49,58,59] and interconnects [23,26,40]. Though cheaper devices (e.g. LEDs and VCSELs) have not been considered seriously for outdoor FSO in the past, recent work shows promising success in reaching longer distances by aggregation of multiple LEDs or VCSELs [1,4].

Acampora *et al.* describes an approach to broadband wireless access networking which consists of small, densely spaced packet switching nodes interconnected by focused directional FSO links in a multihop mesh arrangement [48](Figure 2.1). For a local access network , the responsibility is extending the broadband local access service both economically and reliably. Each node can then serve a client, which may consist of a building containing private branch exchanges (PBXs) and LANs (for fixed-point service), a picocellular base station (for wireless semice), or both. The packet-switching nodes are interconnected by a dense mesh of focused bidirectional free-space-optical links, each fully capable of withstanding atmospheric and mechanical disturbances by virtue of its short physical length. The great virtue of this approach is that very high access capacity can be economically and reliably de-

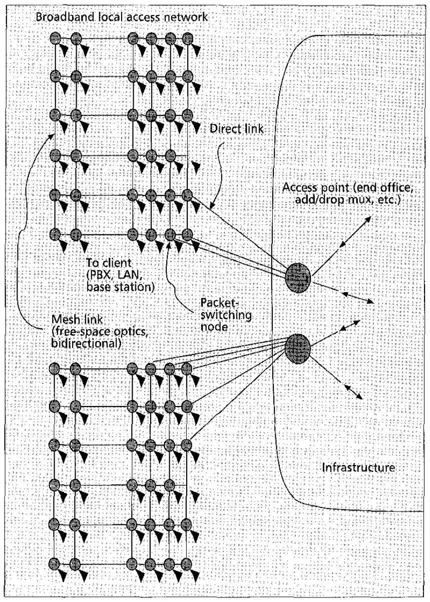

Figure 2.1: Basic architecture of the broadband access network [48]

livered over a wide service area. Many clients can be served by a single access mesh which attaches to the infrastructure at a single access point. In their approach if the density is sufficiently high, the length of each optical link will be sufficiently small that fog attenuation is negligible, and mechanical tolerance are loose as these problems have generally produced disappointing results in the past. Acampora et al.'s work provides the most common use-case of FSO in today's applications; roof-top deployments through a high-powered laser components to reach long distances.

The authors of [44] examine improvements obtained in wireless infrared (IR) communication links when one replaces traditional single-element receivers by imaging receivers abd diffuse transmitters by multibeam (quasi-diffuse) transmitters. They consider both line-of-sight (LOS) and nonline-of-sight (non-LOS) IR links. Obtained power gain is from $13dB$ to $20dB$ while still meeting acceptable bit error rates (10^{-9} with 88% probability) when Space Division Multiple Access (SDMA) is employed in

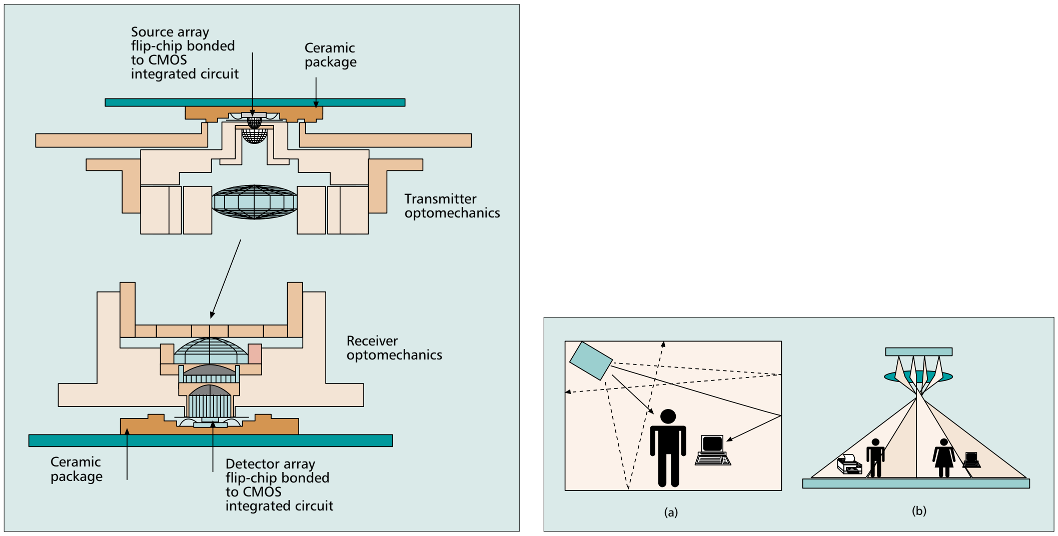

Figure 2.2: System of optomechanics [19]

the absence of cochannel interference. The authors encourage usage of quasi-diffuse (i.e., multiple beams) transmitters since they leverage Space Division Multiple Access (SDMA).

O'Brien *et al.* provides an approach that can be used for in-building optical wireless communication and they argue for the need of an integrated and scalable approach to the fabricating of transceivers [19]. They use devices and components that are suitable for integration. The tracking transmitter and receiver components (diffuse transmitters and multi-cell photo-detectors) have the potential for use in the wide range of network architectures. They fabricated and tested the multi-cell photo-detectors and diffuse transmitters, specifically seven transmitters and seven receivers operating at a wavelength of 980 nm and 1400 nm for eye-safety regulations. They designed transmitters and receivers to transmit 155 Mb/s data using Manchester Encoding. They compare optical access methods: a wide-angle high-power laser emitter scattering from the surfaces in the room to provide an optical ether or using directed line-of-sight paths between transmitter and receiver. In the first approach to transmitter design, although a wider coverage area is achieved, multiple paths between source and receiver cause dispersion of the channel, hence limiting its bandwith (Figure 2.2). They found that the second approach has spatial reuse and directionality advantages, hence provides better data rates while not achieving a blanketing coverage. They conclude that directional optical communication will be dominant in the future beating non-directional optics and radio frequency communication because of its promising bandwidth. They project to overcome the line-of-sight problems in the near future using high precision micro-lenses and highly sensitive arrays of optical detectors.

The last two papers proposed to use relatively directional beams (quasi-diffuse) to take advantage of directionality. Due to limited power of a single source that is being diffused to spread in all directions, these techniques are suitable for small distances (typically tens of meters); and hence they can not be considered for longer distances.

2.3 Mobile Free-Space-Optical Communications

The key limitation of FSO regarding *mobile* communications is the fact that *LOS alignment must be maintained* for communication to take place successfully. Since the optical beam is highly focused, it is not enough if LOS exists: the transmitter and receiver pair should be aligned; and the alignment must be maintained to compensate for any sway or mobility in the mounting structures. Mobile communication using FSO is considered for indoor environments, within a single room, using diffuse optics technology [17,19,21,24,26,34,44,60], including multi-element transmitter and receiver based antennas. Due to limited power of a single source that is being diffused to spread in all directions, these techniques are suitable for small distances (typically 10s of meters), but not suitable for longer distances.

For outdoors, *fixed* FSO communication techniques have been studied to remedy small vibrations [50, 51], swaying of the buildings have been implemented using mechanical auto-tracking [23, 35, 40] or beam steering [61], and interference [10] and noise [30]. LOS scanning, tracking and alignment have also been studied for years in satellite FSO communications [45, 53]. Again, these works considered long-range links, which utilize very narrow beamwidths (typically in the microradian range), and which typically use slow, bulky beam-scanning devices, such as gimballed telescopes driven by servo motors.

We propose to use electronic scanning/steering techniques by leveraging angular diversity of spherical structures covered with multiple transceivers. We built fully-structured prototype of 3-D FSO antenna, which will constitute a lab-based prototype of a demonstrable FSO-MANET work. We plan to make our prototype work at high speeds and longer communication distances.

The idea of using multiple elements/transceivers in FSO communication has been used in interconnects [52], which communicate over very short distance (e.g., cms) within a computer rack or case. The main issues of such multi-element operation are interference (or cross-talk) between adjacent transceivers due to finite divergence of the light beam, and misalignment due to vibration. Multi-element operation has been suggested not only for increasing the capacity of the overall system, but also for achieving robustness due to spatial diversity in the case of misalignment. Our work considers multi-element FSO designs as a general-purpose communication technology working over distances much longer than the interconnects.

2.4 Effects of Directional Communication on Higher Layers

In comparison to RF physical communication characteristics, FSO has critical differences in terms of error behavior, power requirements and different types of hidden node problems. Implications of these physical FSO characteristics on higher layers of the networking stack has been studied in recent years. The majority of the FSO research in higher layers has been on topology construction and maintenance for optical wireless backbone networks [25, 33, 54]. Some work considered dynamic configuration [37], node discovery [55], and hierarchical secure routing [56, 57] in FSO sensor networks. However, no deep investigation of issues and challenges that will be imposed on MANETs by FSO has been performed.

A key FSO characteristic that can be leveraged at higher layers is its *directionality* in communication. Though the concept is similar to RF directional antennas, FSO can provide much more accurate estimations of transmission angle by means of its directionality. Previous work showed that directionality in communication can be effectively used in localization [12, 38], multi-access control [31, 46], and routing [14, 29, 32, 41, 47]. In addition to directionality, our proposed FSO nodes introduce highly-intermittent disconnectivity pattern (i.e. aligned-misaligned pattern) which affects transport performance [11].

In regards to the effect of directional antennas on upper layers, R. Choudhury *et al.* evaluates the performance of DSR (Dynamic Source Routing) using directional antennas [47] and propose modifications. They identify issues that emerge from executing DSR (originally designed for omnidirectional antennas) over directional antennas. Specifically, they observe route request (RREQ) floods of DSR are subject to degraded performance due to directional transmission is not covering as much space as omnidirectional transmission, resulting route reply (RREP) to take longer time. Also, they observed that using directional antennas may not be suitable when the network is dense or linear, because of increased interference. However, the improvement in performance may be encouraging for networks with sparse and random topologies.

2.5 Effects of Atmospheric Conditions on Free-Space-Optics

Free Space Optics has the potential to be future wireless communication technology with fiber-like bandwith under short deployment time. FSO links are difficult to intercept, immune to interference or jamming from external sources, and are not subjected to frequency spectrum regulations. However atmospheric effects can significantly affect FSO signals such as atmospheric turbulence which causes random fluctuations in the irradiance of the received signal, commonly referred to as scintillation. Aerosol scattering effects caused by rain, snow and fog can also degrade the performance of free-space-optical communication systems. Zhu *et al.* describes several communication techniques to mitigate turbulence-induced intensity fluctuations, i.e., signal fading [63]. They propose techniques in order to improve detection efficiency. They use the marjinal distribution of fading to drive a maximum likelihood (ML) symbol-by-symbol detector for systems using on-off keying (OOK) and joint temporal distribution of fading to derive a maximum-likelihood sequence detection (MLSD) for OOK which improves detection efficiency when the instantaneous fading efficiency is unknown but the marjinal statistics are known. To lead a further improvement in detection performance, they apply MLSD in situations where the temporal correlation of fading is known.

Farid *et al.* considers the statistics of photo-electron count in pin photodiodes to measure the [36] performance of signal detection for intensity modulated direct detection optical communication systems through the turbulence atmosphere. The aim is to observe the received signal in the presence of turbulent atmosphere. Electron count and voltage level in the receiver side is observed in order to calculate the performance of the system at the turbulent atmospheric conditions. They observe that scintillation of the received signal caused by atmospheric turbulence results in a photoelectron count that is a conditional poisson process in which the mean count is lognormal.

The authors of [42] demonstrate a technique for modeling the fog droplet size distributions using modified Gamma distribution by considering two radiation fog events recorded in Graz (Austria) and Prague (Check Republic). Their method is useful in the study of fog microphysics and in modeling the fog attenuations for terrestrial FSO links for two cases: When measurement data contains values of attenuations only, or liquid water content only or both at a particular location. For the two case studies, Graz and Prague, they found that the observed behavior of computed modified Gamma distribution parameters are close and consistent. They model the optical attenuations experienced over the terrestrial FSO link installed in Graz, Austria, caused by the continental fog conditions, by a three parameter distribution, called modified gamma drop size distribution (MGDSD), and they adopt two techniques which employ an iterative procedure to compute three distribution parameters of the modified Gamma distribution. The proposed techniques are quite useful in terms of efficiency and yields excellent results while computing optimal parameters for the MGDSD.

Chapter 3

Free-Space-Optics Basics and Prototype

In this chapter, we delve into the details of free-space-optical communication technology basics and details of our prototype.

3.1 Basic FSO Transceiver Systems

It is relatively easy to build a basic FSO transceiver using off-the-shelf components. There are many FSO systems today that are being used in lots of applications including:

- short-term wireless connection for information exchange between two users such as IrDA systems.
- building-to-building connections for high speed network access or campus area networks or wide area networks.

- wireless input or control devices, such as remote controls and wireless game controllers.
- wireless local area networks (WLANs).

The most commonly used components for FSO transmitters are laser diodes (LDs) and light emitting diodes (LEDs). Compared to laser diodes, light emitting diodes are cheaper and they have longer life. They can be modulated at high speeds but the optical power outputs are less than laser diodes. Due to the safety reasons laser diodes can not be used for the indoor optical systems because it can quickly hurt human eye. It can result in permanent blindness if a human retina is faced with a laser source because laser diodes are highly directional radiation sources and can deliver very high power within a small area. On the other hand LEDs consume low power, and they are not highly directional as laser diodes and are safe at higher power compared to lased diodes. This is the key reason why LEDs are preferred for most indoor applications. Power consumption is also big advantage, since LEDs consume low power than lasers; thus, LEDs are preferred for most applications where power adjustments take place.

LEDs emits light energy when a current flows through it. It has the same specifications as regular diodes, except that it will emit light when dissipating energy. The current can only flow one direction and an LED has very low internal resistance that requires using an external limiting resistor to limit the current.

We use infrared LEDs in our prototype which are fabricated from GaA1As and they emit at wavelengths in the range 850-950 nm. They are PN semiconductor junction diodes and the DC optical power output specifications are 1-100 mW at DC forward currents of 20 to 100 mA.

Modulation is a key component in every type of communication. In order to send the information to the receiver, the signal has to be modulated. At the receiving side the incoming signal is demodulated and converted to the appropriate form in order to get meaningful data. Modulation technique effects bandwidth, signal-to-noise-ratio (SNR), power requirements etc. Our FSO transmitters are implemented using an infrared LED which emits optical signal at wavelength of 870 nm. The infrared communication standard has been defined by the IrDA industry-based group. The communication standards that has been developed are well suited for low cost, short range, point-to-point infrared channels. These types of channels operate over a wide range of speeds under a cross-platform environment. Today IrDA standarts have been used to install over millions of low-cost, short range communication systems in laptops, hanheld PCs etc. Today most of the infrared devices use SIR (slow infrared) which can communicate up to 115200 kbps. As an infrared modulation technique pulse-position-modulation (PPM) is well-known which provides high average-power efficiency, but it is more susceptible to intersymbol interference (ISI) than on-off keying (OOK) which is also most used modulation technique that is easy to implement in optical wireless communication.

PPM modulation is used for FIR (Fast Infrared) devices and it can communicate up to 4 Mbps. M message bits are encoded by transmitting a single pulse in one of 2^M possible time shifts. This is repeated every T seconds, such that transmitted bit rate is M/T bits per second. It is primarily useful when it tends to be little or no multipath interference. One of the basic difficulties of implementing this modulation technique is that the receiver must be properly synchronized to align the local clock with the beginning of each symbol. As a result, it is mostly implemented as differential pulse-position modulation, where each pulse position is encoded relative to the previous one, such that the receiver must only measure the difference in the arrival time of successive pulses.

One of the big advantages of PPM is that it is an M-ary modulation technique that can be implemented non-coherently as the transceivers does not need to use a phase locked loop (PLL) to track the phase of the carrier signal and this makes PPM a suitable candidate for optical communications systems, where coherent phase modulation and detection are difficult and expensive.

On-off keying (OOK) is a simple form of amplitude-shift keying (ASK) modulation where the presence of the carrier signal represents binary one for a specific duration, and binary zero is represented for the same duration while the signal is absent. It is more sensitive to noise than frequency shift-keying but it is more spectrally efficient. It is easy to implement and is also used in optical communication systems.

Another type of basic optical wireless communication system are TV remotes (TVR) and different kind of infrared remote controllers, which are the lowest cost systems among all optical wireless technologies. The data rate that they can reach is low (2400-19200 bps) but they are massively available on the market, which is the reason why we selected them for building our prototype. By using these infrared components, a simple FSO transmitter can be implemented and there is a large variety of infrared receivers on the market. The most common technique that is used is Pulse Width Modulation and most of these transmitters emits 38-40 kHz infrared signal. We used this kind of transmitter and receiver in our prototype because they are cheap and easy to build.

3.2 Prototype

By employing commercially available off-the-shelf electronic components, we designed and built a prototype consisting of two main parts: Transceiver circuit and controller circuit. The transceiver circuit has a circular shape which includes both emitting diode and photodiode on itself, as shown in Figure 3.1. The controller circuit contains a microcontroller which is responsible for alignment detection, data transfer and data restoration. The controller circuit also includes the microcontroller and transistor which is responsible for driving emitting diodes at desired modulation frequency and line transceiver which is responsible to convert TTL logic levels to RS232 in order to communicate with a laptop computer.

3.2.1 Transceiver Circuit

Transceiver circuit contains 2 LEDs, one photo-detector and a simple biasing circuit. Schematic of the circuit is shown in Figure 3.2 while picture of the front side and back side is shown in Figure 3.1. We used two LEDs are used to boost the emitted optical power and thereby effective communication range. GaA1As double heterojunction LEDs with peak emission wavelength of 870 nm named TSFF5210 [8] is selected for transmission. TSFF5210 is a high speed infrared emitting diode which has high modulation bandwidth of 23 Mhz with extra high radiant power and radiant intensity while maintaining low forward voltage as well as being suitable for high pulse current operation. Angle of half intensity is ±10 for this LED which makes it suitable for desired node positions. The signal that is sent from microcontroller is modulated by PIC12f615 at 455 kHz and sent to LEDs. TSOP7000 series [8] is used for receiving modulated signals. TSOP7000 is a miniaturized receiver for infrared remote control

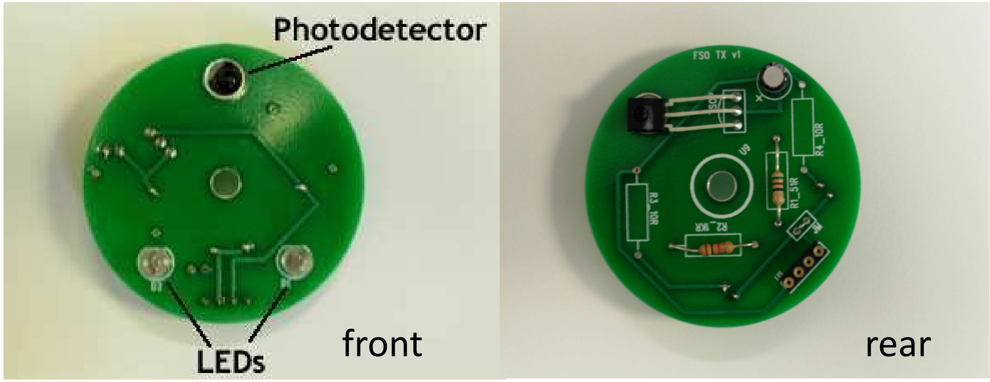

Figure 3.1: Transceiver circuit front and rear view.

and IR data transmission. PIN diode and preamplifier are assembled on lead frame and the epoxy package is designed as IR filter. The demodulated signal can directly be decoded by a microcontroller. The circuit of the TSOP7000 is designed so that disturbance signals are identified and unwanted output pulses due to noise or disturbances are avoided. A bandpass filter, an automatic gain control and an integrator stage is used to suppress such disturbances. The distinguishing marks between data signal and disturbance are carrier frequency, burst length and the envelope duty cycle. The data signal should fulfill the following conditions:

- The carrier frequency should be close to 455 kHz.
- The burst length should be at least $22\mu s$ (10 cycles of the carrier signal) and shorter than $500\mu s$.
- The separation time between two consecutive bursts should be at least $26\mu s$.
- If the data bursts are longer than $500\mu s$ then the envelope duty cycle is limited to 25% .

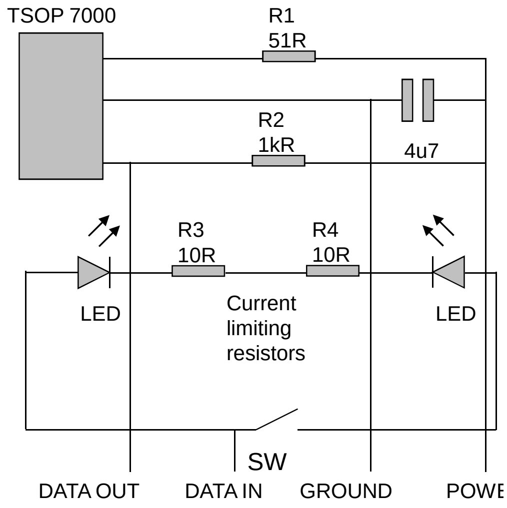

Figure 3.2: Transceiver circuit schematic.

- The duty cycle of the carrier signal (455 kHz) may be between 50% ($1.1\mu s$ pulses) and 10% ($0.2\mu s$ pulses). The lower duty cycle may help to save battery power.

TSOP7000 can communicate up to 19200 bit/s and this is the bottleneck for the prototype's data rate. We used serial communication to transmit data between nodes and serial communication can communicate up to 460800 bit/s. Different types of photo-detectors can be used to increase data bandwidth.

3.2.2 Controller Circuit

Transmission units, data sent and received via transceivers that are controlled by a microcontroller. Microcontroller handles all the alignment protocol in itself and decides whether and alignment is established or not. It also detects if the alignments goes down and buffers data that will be sent upon re-establishment of the alignment. We used PIC24FJ128GA106 a 16 bit microcontroller [7] for implementing the align-

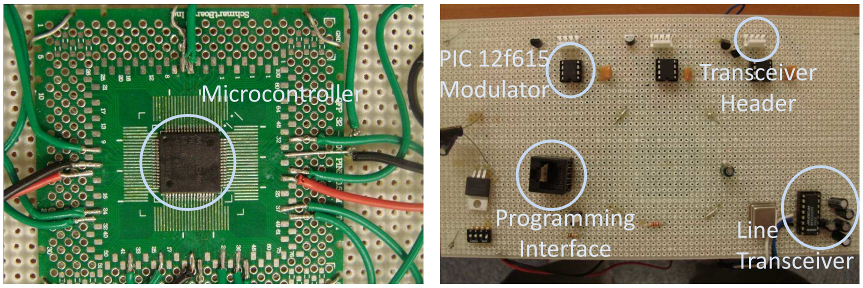

Figure 3.3: Picture of controller circuit.

ment algorithm. Controller circuit as shown in Figure 2 is responsible for searching alignment and data transmission continuity via transceivers simultaneously.

Because each prototype FSO structure has 3 transceivers connected to it and we use RS-232 communication there must be 4 serial port on the microcontroller. Software serial ports can be implemented on a microcontroller's digital input and output pins as the number of digital pin count lets, but this will be without an internal buffer on digital input and output pins. Our alignment and data transmission algorithm needs buffering when the frames received and transmitted, and thus, microcontroller must have built-in serial ports. PIC24FJ128GA106 carries 4 built-in bidirectional serial ports onboard.

3.3 LOS Alignment Protocol for Electronic Steering

Contrary to the traditional mechanical steering mechanisms to manage LOS alignment, alignment protocol by simple electronics, which essentially achieves "electronic steering" use a simplified 3-way handshake protocol to establish alignment between transceivers in LOS of each other. Such an alignment protocol delivers quick and au-

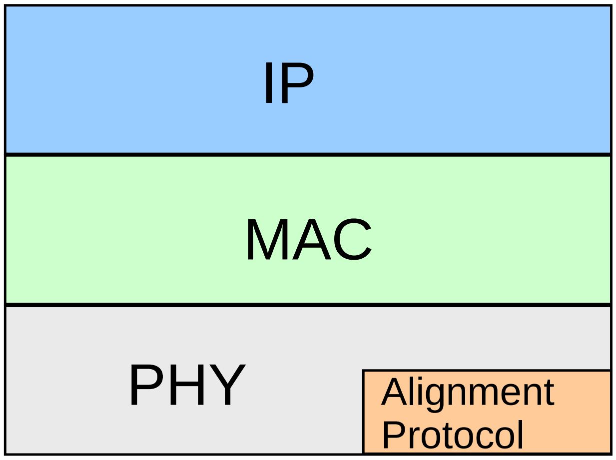

Figure 3.4: Default placement of alignment protocol in protocol stack.

tomatic hand-off of data flows among different transceivers while achieving a virtually omni-directional propagation and spatial reuse at the same time [62].

The main purpose of the alignment protocol is to make alignment process seamless to the higher layers of the protocol stack. Figure 3.4 shows this basic architecture which makes FSO links seem just like any other RF link to the higher layers. It is possible to let higher layers know about the dynamics of the alignment protocol to optimize communication performance for multiple transceivers of the spherical FSO nodes. However, we focus on the proof-of-concept design in Figure 3.4.

The essence of our LOS alignment protocol is to exchange small frames between neighbor multi-element FSO nodes and identify the transceivers that are in line-of-sight of each other. The protocol aims to establish a *bi-directional* optical wireless link and hence uses a simple three-way handshake messaging method for full assurance of the alignment (Figure 3.5). Our alignment protocol uses a small frame (e.g., 4 bytes long), hence a frame does not keep the physical channel busy for too long. A frame starts with a FRAME_START byte, indicating the start of channel usage by another transceiver. SENDER_ID and RECEIVER_ID fields follow the frame indicator. Both bytes are node IDs instead of transceiver IDs. Last byte is the FRAME_TYPE byte that indicates the intention of the sender of this frame. In a frame of type DATA, the fifth byte is the length of the payload. Hence, the payload is variable-length.

There are 4 different types of frames. SYN, SYN_ACK, ACK and DATA. Realignment algorithm starts by sending SYN frames through a particular transceiver (lets assume A.1 on node A). The algorithm keeps sending this initial signal periodically until it receives a SYN_ACK answer to its SYN or it receives a SYN originated from a transceiver on a different node than itself (B.1 on node B). If it receives a SYN, it replies with a SYN_ACK. If it receives a SYN_ACK, it replies with an ACK. For simplicity, let's follow the case in which that A.1 sends a SYN, B.1 replies with SYN_ACK and A.1 replies with an ACK. When A.1 sends out its first ACK frame it changes internal state to ALIGNED with node B and same is true for B when it receives the ACK. At this point, B and A starts exchanging DATA frames. We did not implement an ACK mechanism for DATA frames to keep the protocol simple.

After a period of time (2 seconds, not necessarily idle), alignment timer goes off and changes the state of the interface to SENDING_SYN which starts the alignment process again. This simple alignment process, although exchange a very small number of frames, will disrupt the carried flow and cause drops. The algorithm has been successful in establishing the alignment at the first trial, that is with exchange of only 3 frames.

Although the alignment protocol is fairly straight forward and similar to RTS-CTS-DATA-ACK sequence found in RF MAC implementations, it plays a vital role in detection of available extra physical layer communication channels and it is the key components that makes intermittency of FSO links seamless to the upper layers

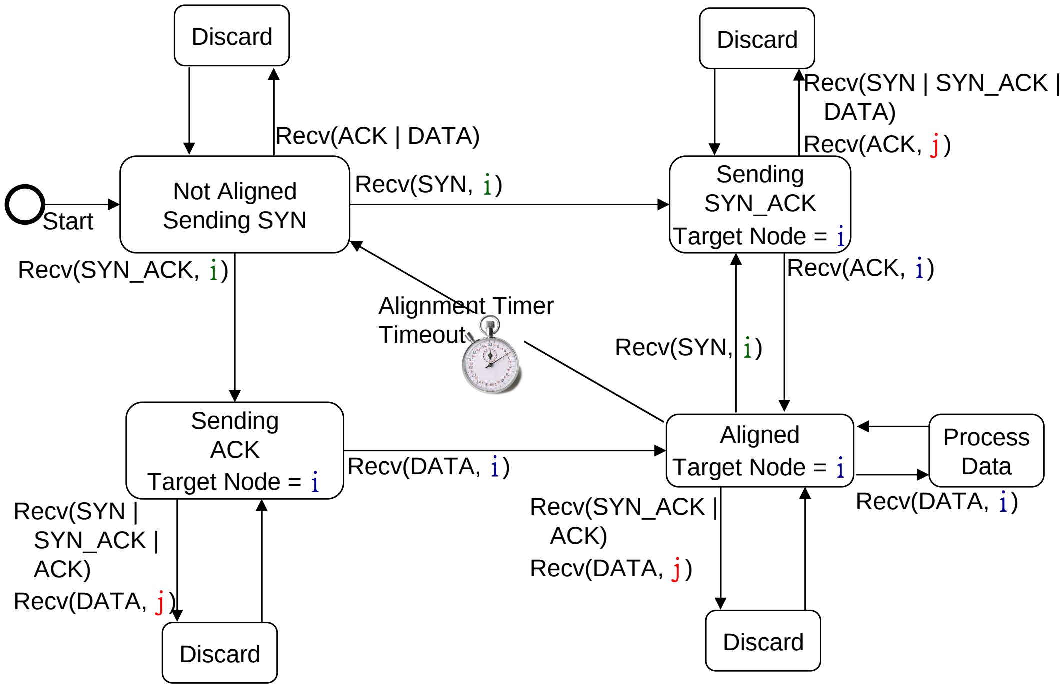

Figure 3.5: State diagram of alignment algorithm.

as shown in Figure 3.4. By implementing a physical layer LOS alignment protocol it also becomes possible to realize solutions such as buffering of “physical layer frames” to make the FSO communication’s intermittency seamless to upper layers.

Chapter 4

Prototype Hardware Setup and Proof-of-Concept Experiments

4.1 Hardware Setup

We began building our prototype using the microcontroller PIC16F877A. PIC16F877A is one of the 8 bit microcontroller family of Microchip company. This microcontroller has one built-in hardware serial port on it. To communicate with a PC via RS-232 using serial communication standard we needed to use two serial ports since one of the serials ports will be connected to the FSO transceiver and the second one will be connected to PC via RS-232. We implemented a software serial port on the microcontroller for the connection to PC via RS-232. The aim of this setup was setting a connection between PC, microcontroller and transceiver. The material list for one FSO node is as follows:

- PIC16F877A
- PIC24FJ128GA106

Figure 4.1: Hardware setup: transceiver is connected to a laptop pc.

- PIC12F615 (For modulation at 455 kHz)
- PN2222 Transistor
- Max232 CPE
- Capacitor
- Transceiver circuit
- 4 pin headers
- 74HC451N Multiplexer/Demultiplexer

To test the transceivers, we first tried a connection by simply connecting the transceiver to a laptop PC. Using hyper terminal on a windows machine we simply echoed an ASCII character and we observed that the transceiver works properly.

Next, we connected the microcontroller PIC16F877A to the PC in order to see that a basic echo program works in this setup using microcontroller. We observed that we can completely echo an ASCII character back to the laptop PCs.

Serial RS-232 communication works with voltages -15V to +15V for high and low. On the other hand TTL logic operates between 0V and +5V. We needed to convert the RS232 levels down to lower levels of 0V-5V range. We used a line transceiver Max232 CPE for converting RS232 levels to TTL levels. In this current setup, shown

Figure 4.2: Hardware setup: laptop pc is connected to the microcontroller.

in Figure 4.2, we verified that one FSO-Node (Node-A) worked properly with the a transceiver and microcontroller.

This current setup (Node-A) is duplicated with another FSO-Node (Node-B) to test communication between two FSO-Nodes. As shown in Figure 4.3, we have two serial communication links at each node called COM-A and COM-B which we implemented on the microcontroller. COM-A is the serial connection between laptop PC and microcontroller, and COM-B is the serial connection between microcontroller and transceiver. COM-A-RX is the link which receives signal from laptop PC to microcontroller, and COM-A-TX is the link which sends signal from microcontroller to the laptop PC. COM-B-RX is the link which receives signal from transceiver to the microcontroller, and COM-B-TX is the link which sends signal from microcontroller to the transceiver. Instead of echoing a character back to laptop PC, we received a pressed key from the keyboard via COM-A-RX, and then we sent this character to the output of COM-B-TX which is connected to LEDs of the transceivers. Thus, we sent the ASCII character to Node-B using LEDs over the transmission medium which is free-space. The ASCII character is received via photo-detector of Node-B which is connected to COM-B-RX again and sent to hyper terminal of Node-B via COM-A-TX. This setup worked properly and we established an FSO link between Node-A and Node-B.

In order to add more transceivers on our prototype we decided to use a multiplexer/demultiplexer which will select the possible transceivers when the transmission

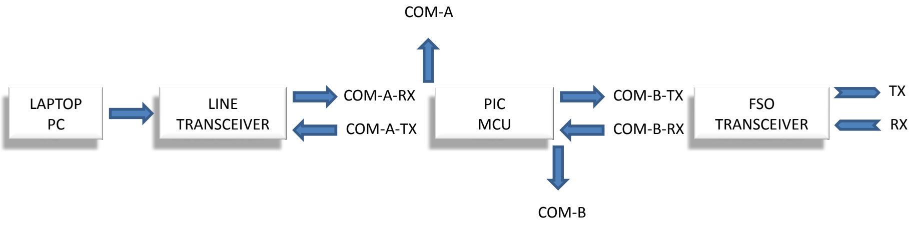

Figure 4.3: Hardware setup: FSO-Node with 1 transceiver and microcontroller.

is going on. This idea does not immediately work with the setup above, because we needed to listen incoming signals from all transceivers simultaneously and we had one serial communication port on our PIC16F877A microcontroller. Selecting one transceiver at a time would make the other transceivers idle and the prototype would search for an alignment signal at a wrong transceiver forever. So, we decided that microcontroller have to handle all selection and alignment algorithm independently. We used 5 byte frame type for implementing our LOS alignment algorithm; and in order to make the alignment algorithm function properly, we needed built-in hardware serial ports. Software implemented serial ports didn't have a buffer; and the first setup which was working with PIC16F877A didn't function when we implemented the alignment algorithm on this microcontroller.

These two problems necessitated using a different kind of microcontroller which has more than one built-in serial hardware ports. We decided to use PIC24FJ128GA106 that is an 16 bit microcontroller of Microchip family. This microcontroller has 4 built-in hardware serial ports on it. To prove the idea of electronic steering mechanism and multi-transceiver FSO system, we needed three transceivers at each node and three nodes for the overall setup. This microcontroller had the needed functionality for a basic proof-of concept setup. So, we used PIC24FJ128GA106 for our prototype and implemented the LOS alignment algorithm on this microcontroller which can control three transceivers simultaneously; and this is the most current setup that we have for our prototype. Adding more transceivers may be possible by using FPGA, smart multiplexers or MIMO systems.

For our implementation we searched available products on the market and first decided to use CCS-C compiler [2] for PIC16F877A. CCS-C is easy to use and program. It contains very user-friendly special functions but it does not have desired functions for PIC24FJ128GA106. We decided to use MPLAB C Compiler when we began to use PIC24FJ128GA106 for our prototype. MPLAB C Compiler is a product of Microchip Company and it has a free demo version for students.

4.2 Proof-of-Concept Experiments

We implemented a simple FSO transceiver and alignment circuit prototype. The design consists of 3 FSO transceivers connected to a circuit board with a microcontroller. Microcontroller connects to a laptop computer (A) through RS-232 serial port. This microcontroller implements the alignment algorithm: it routinely probes for new alignments. This simple prototype is duplicated for 2 other laptop computers (B and C), so that we can establish a flow (file transfer) among the three nodes (Figure 4.4 and 4.9).

Our goal in this initial design is to test the feasibility of an LOS alignment algorithm, and demonstrate that *despite a major change in physical network topology, data phase can be effectively restored upon re-establishment of alignments.* To illustrate these goals, we present 6 experiments. Except last two experiments each experiment lasted 10 seconds and were repeated 10 times for more reliable results. In each experiment, we transfer an image file. We transfer every pixel of the file in one

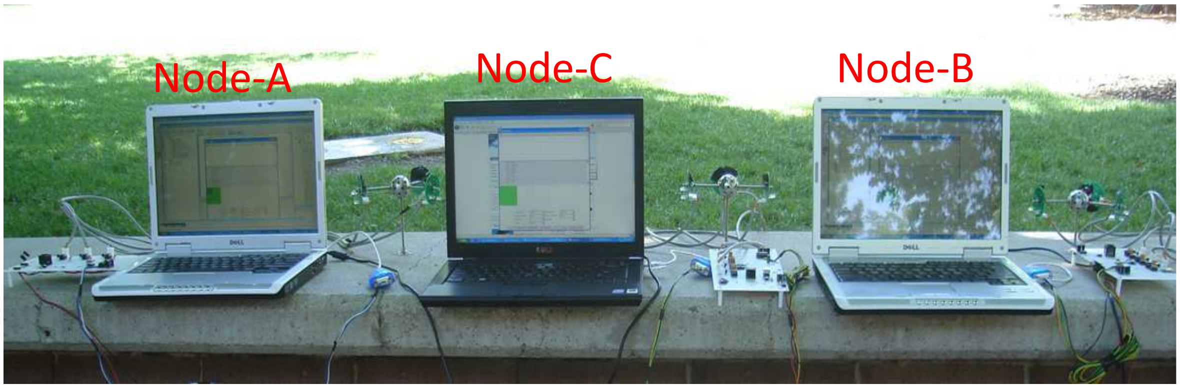

Figure 4.4: Experiment setup: 3 laptops (collinear placement), each with a 3 transceiver optical antenna.

data frame. Hence, a typical data frame consists of 5 bytes: x and y of the pixel and red, green and blue values. The first 3 experiments do not involve mobility.

4.2.1 Baud Rate Experiment

In this experiment the transmission is bi-directional. Node-A and Node-B are placed 1 meter apart from each other. The aim is to observe number of frames that can be sent per second as the baud rate varies. Here we define throughput as number of frames that can be sent in each second. We increased the baud rate from 1200 bps to 38400 bps. We observed that (Figure 4.5) the number of frames that are successfully sent increases as the baud rate is increased. We observed that transmission becomes impossible when the baud rate goes beyond 38400 bps. Thus, 38400 bps baudrate is the upper bound for our transceivers. We used 19200 baud rate level for next experiments.

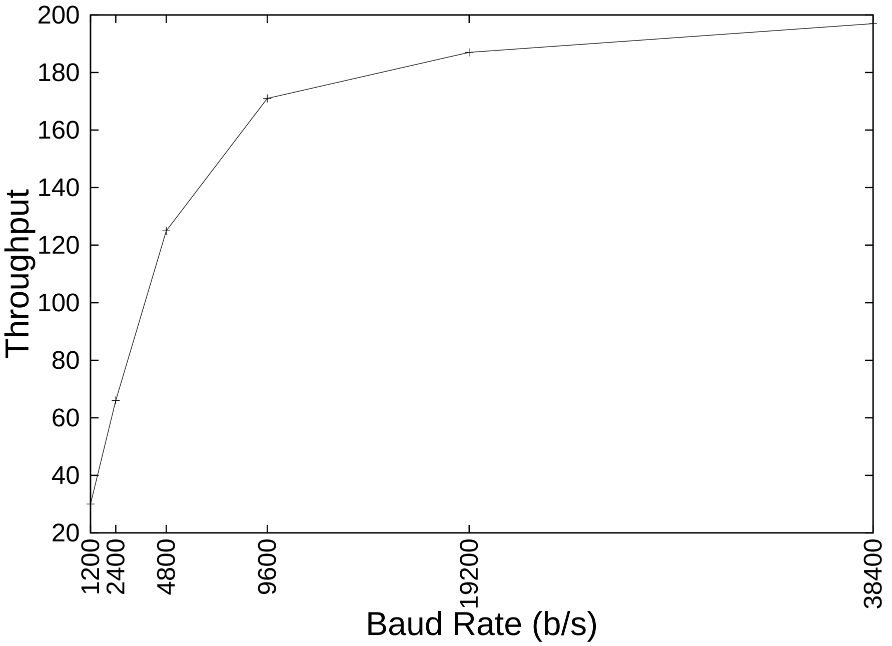

Figure 4.5: Throughput behavior as baud rate varies.

4.2.2 Payload Size Experiment

Similar to the previous experiment, Node-A and Node-B are placed 1 meter apart from each other. The transmission is again bi-directional. The aim is to observe the effect of payload size on frame count that is being sent per seconds and throughput that can be achieved. Here we define throughput as the number of bytes that can be sent in ten seconds. We can formulate our throughput as:

$Throughput = PayloadSize * FrameCount$

Payload size has negative effect on frame count that frame count decreases when payload size is increased. We observed that (Figure 4.6) we achieve maximum throughput when payload size is 15 and frame count is 93. We increased payload size until we reached maximum throughput and we observed that the negative effect of payload size increases on the frame count thus makes throughput decrease after its

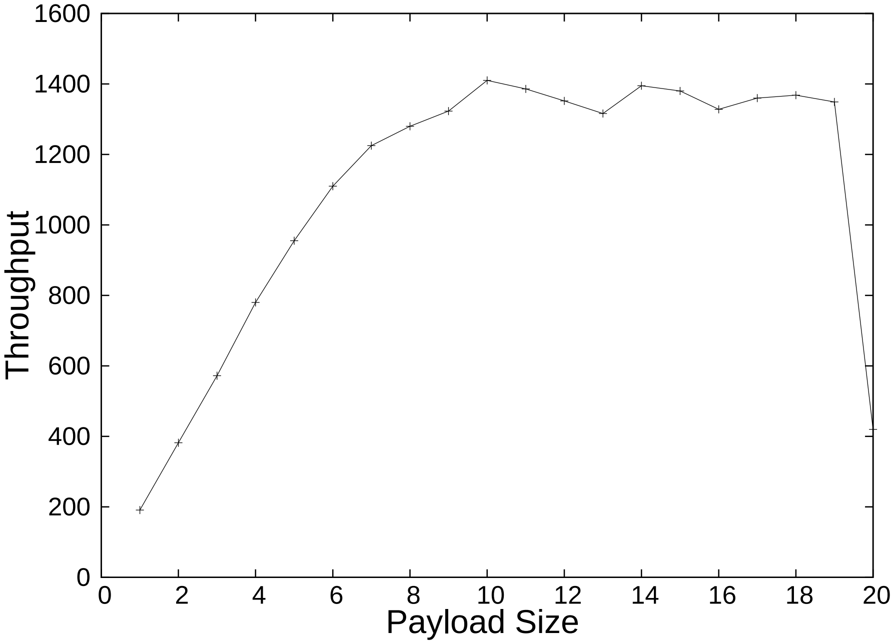

Figure 4.6: Throughput behavior as payload size varies.

maximum value.

4.2.3 Frame Count Experiment

In this experiment we increased frame count that is sent in each alignment interval and observed its effects on the channel usage. We can formulate our channel usage as:

$ChannelUsage{=}100{*}ChannelCapacity/Throughput$

Here the capacity is the number of frames that is sent in 10 seconds and throughput is the number of bytes thats is received in 10 seconds. We found that (Figure 4.7) channel usage increases until it reaches its maximum value, and then decreases until channel gets its saturation due to the change on frame count that is being sent in each second. We achieved maximum channel usage of 97.68% when the

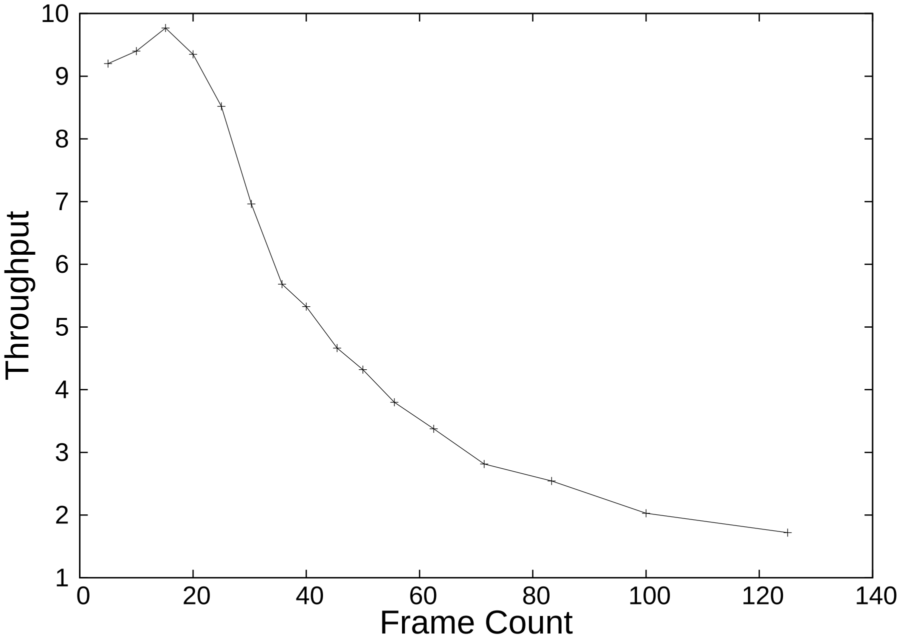

Figure 4.7: Frame count effect on channel usage.

number of frames that is sent is 15. The channel becomes saturated when throughput is 215 (frame in ten seconds).

4.2.4 Distance Experiment

In this experiment we observed throughput behavior as the communication distance varies. We again placed two nodes 1 meter apart from each other for the beginning condition and then increased the distance between the two nodes. We observed that throughput doesn't change until the transmission distance becomes critical for transceivers. We found that (Figure 4.8) critical point is 8 meters. We continued increasing the distance and we found that 9 meters is the last value that transceivers can communicate with each other. Thus our critical interval is between 8th and 9th meter.

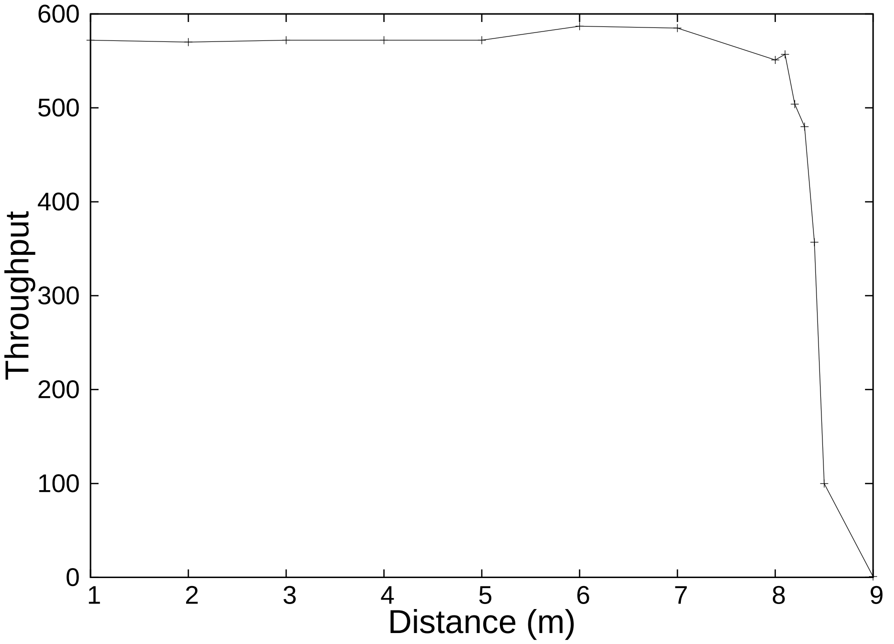

Figure 4.8: Distance effect on throughput.

4.2.5 Stationary Experiments

Stationary experiment is fairly simple: Node-A sends an image file (126 by 126 pixels) to Node-B. The transmission is unidirectional. We found that since the alignment between 2 nodes is re-established every 2 seconds, nodes experience 10% data loss. This experiment reveals a simple improvement: we can delay/cancel re-alignments as long as a data flow is live and remove the 10% overhead totally.

Second experiment is done between two nodes: Node-A and Node-B. In this case, both nodes send an image file of 126x126 pixels to each other. Node-A was able receive 14136 of 15876 pixels. Node-B experienced a similar throughput: 13904 pixels.

Third experiment is conducted using 3 nodes. We placed 3 nodes in a ring topology and started file transfers from Node-A to Node-B and from Node-B to

Figure 4.9: Indoor experiment setup: 3 laptops (collinear placement), each with a 3 transceiver optical antenna.

Node-C and from Node-C to Node-A. In this experiment, *every node was able to utilize its 2 out of 3 transceivers at the same time*, which clearly demonstrates the potential of spatial reuse. At the end of the transmissions, Node-A received 12950, Node-B received 9395 and Node-C received 12755 pixels.

4.2.6 Mobility Experiment

In this experiment, we placed Node-A and Node-B 2 meters apart from each other. Node-C was placed in the middle of the two. Hence, Node-C was able to connect to A and B. However, Node-A and Node-B could not connect to each other when Node C was in between. We transferred an image file of 49 by 49 pixels from Node-C to other two nodes. Transmission went on without significant disruption until the transmission reached the half of the file. We moved Node-C 1 meter away perpendicular to the

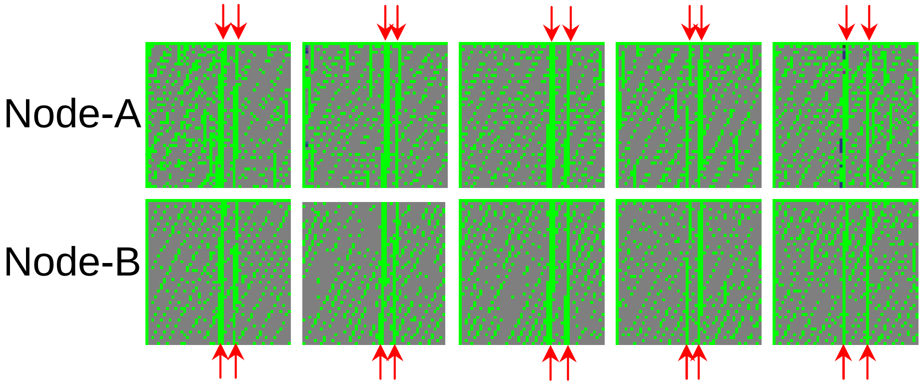

Figure 4.10: Experiment setup with 3 nodes and screen shots of a prototype experiment where transmitting node is mobile.

line between nodes A and B, and waited for 10 seconds. 10 seconds later, we placed Node-C in its original place. Another 10 seconds later, we removed it again. And placed it back after another 10 seconds. We observed that these 10-second disruptions have a vivid effect on the file transfer and can be clearly seen on all 5 iterations of this experiment in Figure 4.10. We saw that Node-C was able to successfully restore the data transmission every time after loosing its alignments. Figure 4.10 shows straight green lines in which the transmitting node gains mobility. Red arrows indicate loss of alignment (and data) due to mobility. Once the mobile node returns to its place, data phase is restored and transmission continues. (Green spots show data loss)

Chapter 5

Conclusions and Future Work

We demonstrated a prototype of a multi-transceiver spherical FSO node which can successfully hand-off multiple data flows between FSO transceivers. We used off-the-shelf components to implement the concept of spherical FSO nodes. We employed micro-controllers to implement a line-of-sight alignment protocol which automatically hands off logical data flows among the physical FSO transceivers. We used infrared LED and photo-detector pairs as the FSO transceivers and showed several experiments using three laptops each with a three-transceiver circular FSO unit. We conclude that FSO communication system can be embroidered with such auto-alignment mechanisms in order to overcome the inherent challenges of FSO directionality. Those mechanisms make FSO an attractive solution for the dense use cases like in a lounge as well as mobile inner-city settings.

FSO technology is affected by building sway, which throws transceivers out of alignment. Manufacturers have mitigated this problem either by increasing the power and widening the light beam or by incorporating mechanical auto-tracking systems which needs careful positioning of transceivers. Our LOS alignment algorithm can solve these problems by electronic steering mechanism, which maintains optical wireless links with minimal disruptions while switching the active transceivers. Electronic steering mechanism makes FSO an attractive approach for mobile communication users for indoor and outdoor environments. A roof top deployment of such a system can communicate with either mobile users or stationary users for innner-city settings.

For multiple agent communication tasks, electronic steering mechanism makes FSO a viable alternative to RF communication as FSO offers throughput of several Gbps to distances of few kilometers. RF is mostly used and preferred for mobile networking mainly due to the requirement of maintaining line-of-sight (LOS) for optical communication. Hence FSO is thought to be not able to serve mobile users. Our electonic steering mechanism makes FSO technology applicable to mobile communications. An advantage of FSO for multiple agent communication is highly directional nature of beams which can be used for localization. Range based localization methods require a higher density (i.e, at least three other localized neighbors). Lower node density localization can be achieved by using directionality information of two GPS-enabled nodes. Optical communication is also a promising approach for localization which requires lower node density and less power compared to other localization techniques such as sonar and laser range finder.

The approach of FSO communication via multi-element antennas has also an attractive potential towards being used as the next generation wireless communication technology because of its high speed modulation capability compared to RF. FSO antennas have less power consumption while omni-directional antennas need more power to send the signal in all directions. We plan to add more transceivers on our prototype and increase the number of nodes beyond three in our FSO-MANET. We also plan to increase the data rate of the prototype and make it especially closer to the Ethernet speeds to bring the desired impact in wireless networks.

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