University of Nevada, Reno

Transceiver Selection for Multi-Element Free-Space-Optical Communications

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Abstract

The focus on wireless networking technologies has always been on radio frequency (RF). However, the capacity of these networks is limited by the availability of the RF spectrum. On the other hand, recent wireless applications have increased the demand for higher speed connections driving the need for higher capacity on the RF spectrum. It is expected that the demand will always stay hungry for more capacity and power, and RF spectrum is close to its saturation and may not be capable of handling future heavy loads. Hence, there is an urgent need for alternative wireless technologies that can complement legacy RF. Recently, Free-Space-Optical (FSO) communication has gained prominence as a technology complementary to RF since it has the potential to deliver wireless communication links at optical-level speeds. FSO transmitters are directional and have the advantage of high-speed modulation. An omni-directional FSO antenna can be built by using multiple transceivers on a spherical structure that will virtually behave like the traditional RF antennas. However, maintenance of line-of-sight (LOS) between transceivers during an ongoing transmission is an important issue that comes with the cost of directionality.

Today, the maintenance of LOS in FSO communications is managed by mechanical steering mechanisms that are not flexible and fast enough to recover the disruptions in a mobile scenario. To remedy this problem first, we propose an electronic steering mechanism and an LOS maintenance algorithm for multi-transceiver FSO structures. The electronic steering mechanism and the LOS algorithm provide

an ability to maintain optical wireless links with minimal disruptions caused by relative mobility of communicating nodes. Second, we explore the possibility of using the directionality of FSO communications for solving the 3-D localization problem in ad-hoc networking environments along with simulations and proof-of-concept prototype experiments. Lastly, we explore ways of making the LOS maintenance algorithm more energy efficient. The basic versions of the electronic steering mechanism and the LOS algorithm recover from disruptions caused by mobility; however, they do so by activating all the transceivers. This is not efficient in terms of circuit design and power consumption. We design an efficient algorithm, which will manage LOS alignments by activating a smaller number of transceivers instead of keeping all the transceivers busy. We focus on transceiver selection mechanisms to select an optimal subset of transceivers in spherical modules covered with multiple directional FSO transceivers. We design, evaluate, and simulate two different transceiver selection algorithms: Single Mode Selection and Two Mode Selection. We conclude by providing performance results of NS-2 simulations, conclusions, and future work.

I dedicate this thesis to my wife and children who have supported me throughout the years of my study, especially in the years that I was working on this thesis.

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Chapter 1

Introduction

Recent proliferation of wireless technologies and choices available to user applications have triggered a tremendous wireless demand, and the wireless nodes are expected to dominate the Internet soon [2, 139]. The availability of wireless resources as substrates has caused an ever-increasing variety of applications [140]. Recent reports show that usage of mobile Web [29] and Wi-Fi by smartphones is increasing sharply. Accommodating this growing wireless demand with cellular capacity does not seem possible in the long run. Further, the capacity gap between radio frequency (RF) wireless and optical fiber (wired) network speeds will remain huge because of the limited availability of RF spectrum [65]. Though efforts for an all-optical Internet [168] will likely provide cost-effective solutions to the last-mile problem within the wire line context, high-speed Internet availability for mobile ad hoc nodes is still mainly driven by the RF spectrum saturation and spectral efficiency gains through innovative techniques such as hierarchical cooperative [126] or OFDM-supported MIMO [86]. As the RF spectrum is getting scarcer, the push for more wireless bandwidth is driving wireless technologies in alternative spectrum bands into the networking field [38].

Free-space-optical (FSO), a.k.a. optical wireless, communications has been one of these technologies complementary to the traditional RF.

FSO communications is becoming more of a candidate for core networking technology rather than its traditional treatment as a sub network. Recent research explored the potential for free-space-optical (FSO) communications in the context of high-speed mobile ad-hoc and opportunistic networking. FSO transceivers are cheap (less than $1), small, low weight (less than 1gm), amenable to dense integration (more than 1000 transceivers possible in 1 sqft), are 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 micro radian beam spread) and operate in large swathes of unlicensed spectrum amenable to wavelength-division multiplexing (infrared/visible) as depicted in Figure 3.2. Unlicensed huge optical spectrum as well as much lower power-per-bit properties of FSO communications, make it a great opportunity for future spectrum-scarce mobile networks and power-hungry sensor networks [89].

To counteract these numerous advantages, FSO communication requires clear line-of-sight (LOS), and LOS alignment between the transmitter and receiver for communication. Due to high directionality of FSO beams, maintenance of LOS between transceivers during an on-going transmission is a critical issue. FSO communication also suffers from beam spread with distance (tradeoff between per-channel bit-rate and power) and unreliability during bad weather, especially fog.

In order for the FSO to become a complementary communication medium for mobile wireless access, the key problem to be solved is its vulnerability against mobility [38]. The key limitation of FSO regarding *mobile* communications is the fact

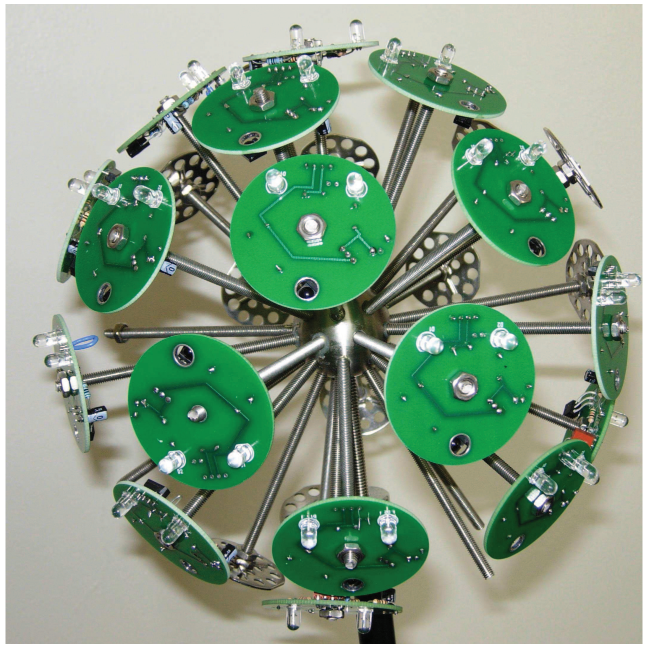


Figure 1.1: 3-D optical antenna design.

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 the receiver must be aligned; and the alignment must be maintained to compensate for any sway or mobility in the nodes. Traditional solution approach to this problem of FSO communications has been to employ highly sensitive mechanical steering and tracking equipment with a powerful single transmitter such as a laser. The mechanical equipment physically rotates the transceiver to maintain the LOS alignment with the other device, which is also applying the same mechanical steering procedure. This approach can achieve establishing a wireless link even if the two communicating devices/nodes are moving with respect to each other. However, it produces device packages that are typically bulky in size, and thus, makes it very hard to develop portable FSO communication devices.

Recent research has shown that FSO mobile ad-hoc networks (FSO-MANETs) can be possible by means of "optical antennas" [113, 174], 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). By using the directionality of FSO transceivers unlike the the traditional mechanical steering mechanisms for LOS management, we used a simple handshaking protocol to "electronically steer" the LOS alignment onto the correct transceiver in our previous study focusing on such spherical FSO structure (like the one shown in Figure 1.1) with multiple transceivers. We provided proof-of-concept experiment results showing feasibility of achieving optical wireless link over such multi-transceiver structures. The design of the prototype consisted of 3 FSO transceivers connected to a circuit board with a microcontroller and microcontroller is connected to a laptop computer through RS-232 serial port. The concept showed 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 also demonstrated another prototype to improve the concept of our first study by testing the feasibility of our LOS algorithm for a multimedia application. Therefore, the prototype consisted of different controller boards and faster transceivers. We transferred a voice file to test the feasibility of our LOS protocol for a basic multimedia application. The LOS detection and establishment protocol makes it possible to send localization packets to the appropriate transceiver on our prototype. Therefore, the prototype can be used for an FSO based localization technique to show the validity of our localization approach even with three transceivers per node.

Our study of electronic steering [150] has shown that there is an urgent need for a selection mechanism for the transceivers since activating many transceivers for the line-of-sight detection and alignment of neighbor nodes on a spherical FSO node is not efficient. When multiple transceivers are deployed on a spherical FSO node, maintaining the power consumption in realistic regions is a major problem. Another problem is the hardware limitations of the current controllers. Providing a transmission medium for multiple transceivers requires many I/O interfaces since implementing many I/O interfaces on a controller board is not cost effective. Such system may not be scalable when packaging multiple transceivers on a spherical structure is considered for a multi-dimensional optical antenna. The selection strategy becomes more challenging when this limitation is considered for an ad-hoc environment where many FSO nodes with multiple transceivers are communicating with each other. Therefore, the challenge is to select an optimal subset and to decide on an optimal order of how to incorporate the transceivers in the network for fast and efficient alignment. Selection strategy of the transceivers must also maintain the LOS alignment under disruptions that are caused by the mobility of the communicating nodes since there is an uncertainty of the location of the mobile nodes in 3-D space. In such scenarios, the technique of the determining uncertainty can be based on approximations by different distribution models such as Gaussian distribution. There is also need for smart and fast selection mechanisms that will select the optimal subset of transceivers to establish the alignments between the neighbor nodes.

1.1 Contributions

Contributions of this dissertation are as follows: conclusions derived from extensive simulation studies and confirmation from a proof-of-concept prototype. On the simulation front, this dissertation builds upon the contributions of [174] in which the concept of spherical antenna was first revealed. Our contributions in this dissertation include:

- proof-of-concept prototype to demonstrate the effectiveness of our approach [1].
- optical-only 3-D localization techniques, and [2].
- transceiver selection mechanisms for assessment of throughput characteristics of FSO-MANETs,

1.2 Dissertation Organization

This dissertation is organized as follows: In Chapter 2, we provide a summary of relevant major research efforts in the literature, their common use cases, problems, and solutions in those fields. We cover representative papers in the fields of High-Speed FSO Networks with High Spatial Reuse and FSO for High-Altitude vs. Low-Altitudes to cover how mobile FSO has been considered in the past and provide insight on how researchers coped with directionality and sectored communication instead of an omnidirectional one. Later, we provide a survey for the effects of atmospheric conditions on FSO and outdoor ultraviolet FSO communication. We also provide a survey on visible light and infrared communication to show the prominence that

[1] This contribution was achieved in collaboration with Dr. Mehmet Bilgi.

[2] This contribution was achieved in collaboration with Dr. Mehmet Bilgi.

FSO has gained recently. Further, we provide a survey on localization techniques for MANETs: range-only, orientation-only, and hybrid techniques. Lastly, we cover transceiver/channel selection mechanisms for multi-transceiver mobile structures.

Chapter 3 covers the details of our prototypes with a basic explanation of related technology and LOS alignment protocol. In this chapter, we also cover the performance of a voice file transfer over LOS protocol and localization technique. Chapter 4 extends the usage of FSO to the well-known localization problem and emphasizes the directionality benefits that are inherent to FSO by sketching a cross-layer design to abstract the directionality information and present it to upper layers. We provide a light-weight localization algorithm that does not need any additional extra hardware than the FSO hardware and requires a small number of anchor nodes that know their location initially. Chapter 5 covers the experimentation details of our proof-of-concept prototype that can handle multiple simultaneous data streams targeted to different neighbors. We present set of mobility experiments that proves the feasibility of using multiple transceivers on FSO networks. We also provide set of voice file transfer experiments to show the performance of LOS protocol. Further, we provide basic localization experiments to conform simulations results of our localization approach. Chapter 6 presents our design of transceiver selection mechanism and simulation results in mobile ad-hoc scenarios. We present a thorough simulation study where we investigate the effect of divergence angle, transceiver number, and alignment interval. Finally, in Chapter 7, we conclude our work and provide our intuition about future directions.

Chapter 2

Literature Survey

This chapter summarizes the literature background of our work with Free-Space-Optical communications. FSO-MANETs related work in the literature can be categorized into eight main groups:

- High-Speed FSO Networks with High Spatial Reuse,
- FSO usage for High-Altitude vs. Low-Altitude
- Mobile FSO Communications,
- Effects of Atmospheric Conditions on FSO
- Outdoor Ultraviolet FSO Communication
- FSO communication: Visible vs. Infrared
- Localization in MANETs
- Transceiver/Channel Selection Mechanisms for Multi-Transceiver Mobile Structures

2.1 High-Speed FSO Networks with High Spatial Reuse

2.1.1 Demand for High Speed Applications

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 [14] 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 fiber optic communication have worldwide acceptance and it is the most capable of high speed data transmission. 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 [61]. 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 flexible, easy-to-install and practical links.

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.

2.1.2 FSO Wireless Mesh Networks

FSO technology has the potential to facilitate intensive bandwidth applications such as high-speed data transfer and high definition video conferencing. FSOC for wireless mesh networks is mainly considered for rooftop installations where point-to-point or point-to-multipoint architectures are established and limited spatial reuse or redundancy is achieved through one primary beam and some backup beams. This kind of FSO network in mainly suited for ultra-broadband last mile access and residential services [141]. While point-to-point architectures operate at longer distances (2-4 kilometers), mesh FSO architectures operate over shorter distances with less throughput compared to point-to-point systems [5].

Success of FSO for ultra-long distances is due to the fact that FSO transmitters are highly directional and can dissipate power in a focused manner rather than omni-directional spread as in RF signals. This directionality comes with a cost of LOS alignment problem, which requires smart mechanisms to manage LOS among transceivers during an ongoing transmission. Traditionally this has been done via mechanical steering techniques, which are very expensive and require high maintenance and sensitive equipment. Further, since they are essentially solutions targeted to solving limited physical movement, mechanical steering techniques are not fast enough to recover from disruptions caused by mobility. Majority of these steering and tracking methods are focused on point-to-point applications: Terrestrial last-mile, deep space [53], and building-top installations where limited spatial reuse or redundancy is achieved through one primary beam and some backup beams. Scenarios involving multi-point-to-multi-point communication are not considered by these mechanical steering approaches since the overall optimization problem becomes much more complicated in selecting which neighbor to align to. Hence, this kind of FSO deployment is typically a mesh network installation where the tracking/steering problem is reduced to maintaining alignment with one other neighbor.

Such multi-point deployments are mostly used for establishing a stationary backbone network with high throughput and mobility has been impractical due to unavailability of mechanisms that achieve automatic establishment of LOS alignment among mobile neighbors. Each neighbor has an optical access switch and the building itself provides an additional Ethernet stream. This provides the ability of sending beam to another building, which has its own local area network. Buildings can contain multiple FSO systems, direct the beam to other buildings, and establish a mesh network. This kind of last-mile FSO usage eliminates the need to lay cable, especially in geographically challenging environments while serving a large number of end nodes, each with little bandwidth requirements. The main problem in such scenarios has been the building sway and vibrations since the FSOC equipment used for these networks are expected to perform at very high speeds, and thus, are typically very sensitive to misalignments. Various techniques have been developed for stationary deployments of FSO to tolerate small vibrations [36], swaying of the buildings and scintillation, using mechanical auto-tracking [35, 47, 114] or beam steering [164].

Other research issues for FSO mesh networks have been similar to the ones in traditional mesh networking such as topology control. Most of the topology construction and maintenance techniques aim to optimize a network-wide metric such as network throughput, robustness to failures, or delay [69, 81, 156]. Interesting issues arise when hybrid FSO/RF meshes are to be constructed. FSO networks can be used for the long distances at higher speeds with low interference and high security providing the quality of services required by the end users. The flexibility and scalability of reconfiguration based on the changes in traffic and node positions provides a good advantage of using FSO for wireless backbone networks. However, obscuration due to atmospheric conditions serves as the bottleneck in this scheme. The problem can be solved by using hybrid FSO/RF meshes where RF links serve for the backup when FSO is obscured. In order to achieve such kind of topology deployment some problems should be taken into consideration: FSO transceivers are expensive and the deployment should be in an effective way to achieve maximum performance. This consideration brings the problem of topology control in FSO/RF mesh networks. Kashyap et al. studied the topology control and routing problems in FSO backbone networks and proposed some algorithms in order to achieve better performances [92]. In their model with a limitation of the number of transmitters and receivers at each node, they assume that for a given transmitter, receiver pair, a transmitter can only transmit to only one receiver at any given point, and receiver can only receive from one transmitter. Then goal of the study is to maximize the throughput while routing the traffic profile. They propose different algorithms for both single and multi-path topology structures to obtain near optimal solutions since the problem is NP-Hard. Kyle et al. follows the similar pattern by focusing on a graph theoretic framework [75]. Since their problem space is NP-Hard, they propose two different algorithms to increase the delivery of maximal traffic flow across the network. Their algorithms include forming a minimum spanning tree (MST) or traveling salesman path (TSP) to guarantee the network's connectivity and connecting node pairs iteratively based on an recast metric with the constraint of node degree. Their algorithms produce optimal or close-to-optimal solutions. Compared to work in [92], the proposed algorithms outperform in traffic delivery but, they have similar performance in network reliability. However, for larger networks these ideas (exhaustive search or an integer programming) become impractical. In the space of realistic dynamic scenarios, Grumani et al. propose a network of hybrid nodes with multiple transceivers and associations [77]. In the case of a failure, reconfiguration takes place with alternate FSO paths where these paths are established and prioritized through multiple associations. This kind of topology mechanism maintains the optical connection for longer periods of time, which also increases the efficiency, and performance of the network.

2.1.3 Divergence Angle and Channel Gain Tradeoffs

The tradeoff between wireless beam directionality and diversity has been an attractive research topic [136] spanning various parts of the electromagnetic spectrum. Compared to an omnidirectional antenna, a directional antenna can perform better transmit and receive gain for a targeted direction also enabling to deliver better immunity from channel interference [58, 96, 137, 138, 166, 167]. In a directional communication scheme, when the mobility of the nodes must be taken into account the directionality must be steered appropriately for the link persistence. Steering must be done in such a way that connectivity can be preserved to the appropriate node seamlessly.

Navda et al. [115] explored the use of directional antennas and beam steering techniques to improve performance of 802.11 links for the scenarios where access points (APs) and moving vehicles are involved to communicate. The aim was to maximize the throughput by selecting the best AP and beam combination for a drive given the information path. In comparison to an omnidirectional antenna, the authors achieved better throughput at an order of 2-4, improved connectivity duration more than a factor of 2, and 15dB improved SNR compared to an omnidirectional scheme. Ramachandran et al. [136] followed with a similar study where they combined both directionality and base station diversity for improving the uplink connectivity of mobile clients. They achieved an uplink increase up to 154% over pure beam-steering and 45% over pure base station diversity. Further improvements were attained by consideration of link layer multicasting with switched beam-forming antennas [157]. For indoor directional communication, phased arrays were to increase spatial reuse by optimizing the placement of directional antennas to achieve maximized overall network capacity [106].

2.1.4 Directionality and Its Effects on Higher Layers

In comparison to RF communication characteristics, FSO has critical differences in terms of error behavior, power requirements and different types of hidden node problems. An important FSOC characteristic is the directionality in communication similar to RF directional antennas. FSO transmitters can be directional than directional RF counterparts can. Perhaps, the key differentiating property of the directionality of FSO transmitters is the fact that they have much smaller form factors than RF counterparts, and many of them can be packaged into very small volumes. Different than RF directional antennas, each FSO transceiver can be made to cover a tiny angle as small as a few milliradian.

Such high directionality has can be leveraged at higher layers via simple abstractions. For instance, a much better estimation of angle-of-arrival (AoA) is possible by assigning each FSO transceiver to an arrival angle. AoA estimation has not been possible in omnidirectional RF transceivers, and thus the traditional localization techniques used signal strength estimations. Recent work showed that FSO-based localization is possible by using multi-transceiver FSO structures capable of AoA estimation with potentially better accuracy depending on the divergence angle of the used transceivers [33, 43, 46, 88].

In [134], authors design a directional MAC protocol that adapts key ideas from IEEE 802.11 MAC to a hybrid system with both omni and directional transceivers. A node is able to steer the antenna to point to a desired angle. For this *Simple Directional MAC (DMAC)* approach, they implemented RTS and CTS signaling in directional mode. Similar to the Network Allocation Vector (NAV) in 802.11, a directional version is introduced (DNAV) to keep track of allocation of the time domain and *space domain with a local sense of direction.* A node looks up entries from this table whenever it needs to send an RTS to a specific direction. They found that the hidden terminal problem in 802.11 MAC reveals itself in two new forms. First, because the gain of a directional and an omnidirectional antenna with the same transmit power are different (i.e., directional gain is greater), sender and receiver nodes with transmit and receive gains of G^d (directional gain) and G^o (omnidirectional gain), respectively, may be out of each other's range, but may be within range if they both transmit and receive with gain G^d. Secondly, a node that participates in an ongoing transmission (nodes A and B, Figure 2.1) will not hear RTS/CTS frames (exchanged with C and D) since its antenna is directed to a specific point. Upon completion of its transmission, the two nodes, A and B, are potential interferers to

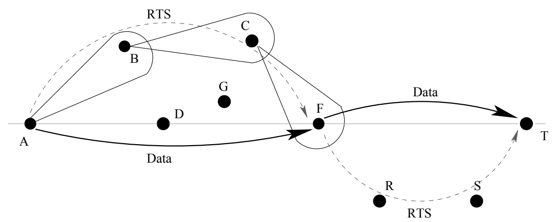


Figure 2.1: Multi-Hop RTS [57].

the nodes that are around them (C and D). In their multi-hop RTS based algorithm (MMAC), authors propose that when two nodes wish to communicate directly in one hop via their directional antennas instead of through multiple hops via their omnidirectional antennas, the sender node sends out a multi-hop RTS frame through its omnidirectional antenna. Upon reception of this frame, the destination node can respond with direct CTS through its directional antenna. Clearly, the multi-hop RTS frame has to be treated with high priority at all the nodes along its way to the destination node. Although this is possible, it has interesting implications on the surrounding nodes. For instance, an RTS may not mean silence for an unintended receiver as it used to mean in the classical RTS-CTS-DATA-ACK cycle of 802.11 MAC since all last three steps are now directional and their unintended recipients are a much smaller subset of their omnidirectional counterpart while a multi-hop RTS has a much larger unintended receiver set of nodes. Additionally, it is clear that RTS transmission and reception are no longer atomic and this may cause time stamping issues for that *exteded/retracted* collusion domain of the network. A slightly smarter way to select sectored antennas for RTS/CTS exchange is to gradually learn if there are nodes residing in the coverage areas of those antennas [80]. In this approach, only the antennas that can reach an immediate neighbor are included into the signaling.

Additionally, Choudhury *et al.* evaluate the performance of DSR (Dynamic Source Routing) using directional antennas in [56]. They identify issues that emerge from executing DSR (originally designed for omnidirectional antennas) over directional antennas. They observe that route request (RREQ) floods of DSR are subject to degraded performance due to directional transmission and do not cover as much space as omnidirectional transmission. This makes route reply (RREP) take a longer amount of time and this in turn degrades the overall performance of the routing protocol.

2.1.5 Capacity Scaling

One of the main motivations of FSOC is the possibility of high spatial reuse by leveraging directionality of transceivers. The capacity of RF-based multi-hop of mobile ad-hoc networks (MANETs) is known to be not scaling, since the per-node throughput in such networks reduces when there is an increase in the number of actively communicating nodes. RF per-node throughput scales with $\sqrt{n}$ as the number of nodes, n, grows since RF interference dominates the throughput behavior because of the omnidirectional propagation [76]. Kumar et al. showed that the $O(1/\sqrt{n})$ value is achieved for an optimal node placement and communication pattern. Extensions to their work were performed [74, 104] including mobility scenarios. The experiments showed that average long-term throughput per source-destination pairs can be kept constant under some boundaries such as exploiting mobility to keep data transfer local, and transmitting only when the transmitter and receiver are close to each other in such a way that the resource usage and interference can be reduced. Both studies in [74] and [104] showed that per node throughput stays roughly constant as the network size grows, however, with significant constraints on topology or mobility.

Later, in [127], optimal capacity scaling was achieved by using intelligent node cooperation and distributed MIMO (multiple input multiple output). The model used in [127] is based on three key ideas: MIMO for long-range spatial multiplexing, local transmit and cooperation to maximize spatial reuse, and intra-cluster cooperation, which enables hierarchical cooperation in smaller network. They showed that when small path loss exponent α is in (2, 3], hierarchical cooperative communication is order optimal and outperforms the multi-hop communication; and for large path-loss exponents $\alpha > 3$, multi-hop communication is order optimal. Similar work was done by the authors of [118, 119] where capacity scaling is considered for extended arbitrary node placement instead of random extended placement in [127] and [76]. The authors achieved the same results for α being in (2, 3], however their results differed for large path loss exponents showing that the scaling depends on the regularity of node placement. Similar works followed by the authors of [120] by considering arbitrary traffic patterns in arbitrarily placed extended wireless networks and define some sufficient conditions for the order of optimality of multi-hop communications covering all traffic patterns for $n \times n$ dimensional capacity region. Under the conditions of their network and traffic model considering their sufficient conditions they show that for exponential power decay multi-hop communication is order optimal regardless of node placement and traffic requirements.

FSOC has much more potential for capacity scaling of multi-hop wireless networks or MANETs, as shown in recent studies [108]. Authors perform two different experiments and compare per-node and overall network throughput results with the same RF scenarios. First, they increase the numbers of nodes in a confined area and keep other parameters same. Second, they increase the area size and keep the number of nodes and all the other parameters the same. In the first scenario they observe that the drop in throughput is much more significant in RF scenario compared to FSO scenario due to the fact that interference starts to dominate the channel accessibility in a highly dense omnidirectional setting. In the second scenario, they observe an increase in the throughput while node density is decreasing. This reflects that the initial node density was still high to cause interference, which reduces when the area is enlarged. When they are further enlarged, FSO starts to experience coverage issues and the throughput drops as a result.

2.2 High-Altitude vs. Low-Altitude

2.2.1 Space and Satellite Communications

FSO technology has been used in different applications including space and satellite communications. Focus of these studies has been building point-to-point communications using highly expensive materials (e.g., mechanical steering mechanisms and lasers) to reach long distances. Based on Chan's study in [52], If readily deployed, FSO is capable of high capacity, low power consumption, available in small sizes and low costs. However, three problems need to be considered for a successful implementation on FSO: spatial acquisition and tracking over very narrow beam optical beams, design of a robust and stable optical and mechanical thermal system and design of a robust lightweight and high-speed optical communications subsystem. Further, a ten year history of optical wireless links for intra-satellite communication is given in [37]. Based on these study, authors propose that use-off-off the shelf devices require extensive analysis in order to fully applicable in the field of space communication and optical wireless technology will not be used until dedicated circuits such as mixed analog digital ACICs are developed. On the other hand, optical wireless is a promising 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.

2.2.2 Terrestrial Networks

Free-space-optical (FSO) wireless, communication technologies use high-powered lasers and expensive components to reach long distances. Thus, the 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 [67, 165]. Main target application of these FSO technologies has been to serve commercial point-to-point links which can operate 155 Mbps to 10 Gbps, from 300 meters to 7 kilometers (e.g., [5,11,23])in terrestrial last mile applications and in infrared indoor LANs [64,82,141,142,160,165] and interconnects [67,70,109]. As an example, Canon [21] manufactures four different models of FSO transceivers capable of communicating 25 Mbps to 1.485 Gbps at 20 to 2000 meters of transmission range with a mechanical auto-tracking system which helps to manage the data transmission due to different environmental conditions such as building sway, wind, and temperature values. Another supplier MRV [25] announced the line-of-sight TereScope 10GE which is a 10 Gigabit Ethernet FSO system. MRV also has previous TS series capable of transmitting at 10 Mbps to 1.5 Gbps with up to a communication distance of 7 kms. Additionally, fSONA [5] and Lightpointe [23] announced different transceiver series that are capable of communicating at 2.5 Gbps with varying distances. 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

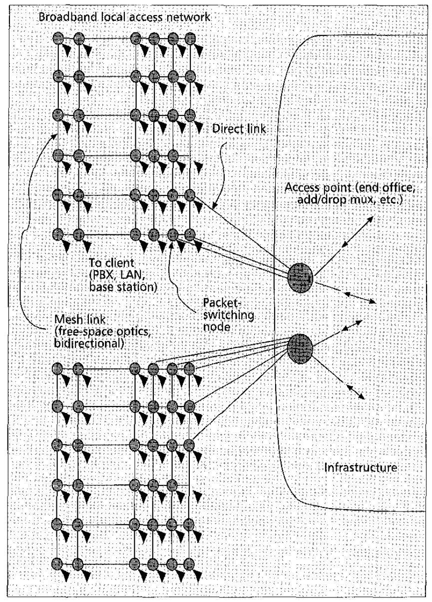


Figure 2.2: Basic architecture of the broadband access network [141]

distances by aggregation of multiple LEDs or VCSELs [1,8]. Compared with lasers or VCSELs, LEDs are modulated at lower speeds (up to 155 Mbps) but they are cheap, small, low weight, consume low power, and have longer lifetime. Most terrestrial FSO technologies (e.g., enterprise connectivity, last mile access network, and backup links) use infrared (IR) frequency band due to eye safety issues. Infrared wireless is a very simple form of FSO communication technology. Most infrared designs use LEDs as transmitters [22]. Infrared FSO links can be implemented using infrared laser light, but low-data-rate communication over short distances mostly employ LEDs. Maximum range for LED-based 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.

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 multi-hop mesh arrangement [141](Figure 2.2). 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 Pico cellular 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 delivered 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.

2.3 Mobile Free-Space-Optical Communications

2.3.1 Mobility: Angular Diversity, Diffuse Optics

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

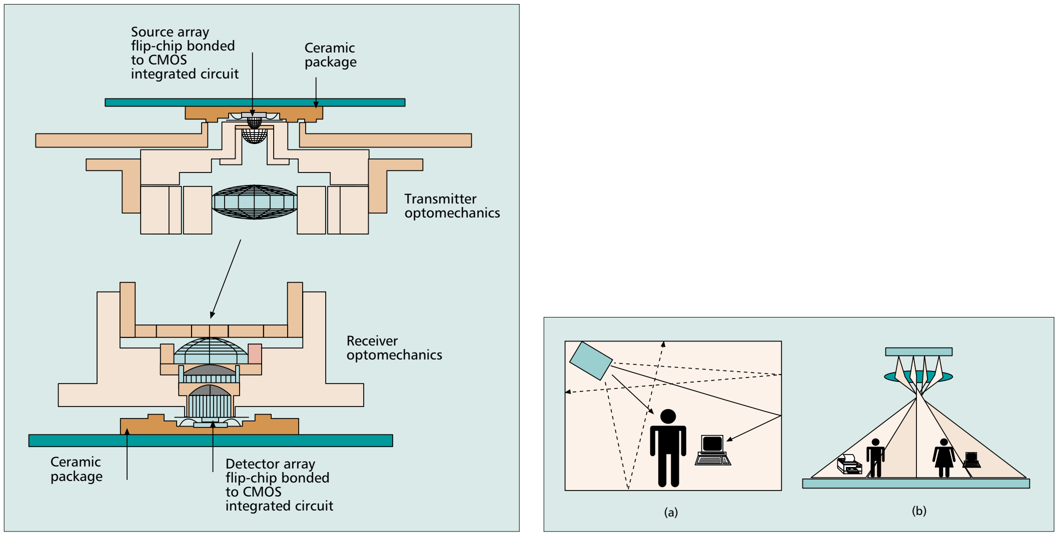


Figure 2.3: System of optomechanics [63]

FSO is considered for indoor environments, within a single room, using diffuse optics technology [60, 63, 64, 68, 70, 82, 128, 170], 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.

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 [63]. 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 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 bandwidth (Figure 2.3). 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 authors of [128] examine improvements obtained in wireless infrared (IR) communication links when one replaces traditional single-element receivers by imaging receivers and diffuse transmitters by multi-beam (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 the absence of co-channel interference. The authors encourage usage of quasi-diffuse (i.e., multiple beams) transmitters since they leverage Space Division Multiple Access (SDMA).

FSO mobile ad-hoc networks (FSO-MANETs) can be possible by means of such multi-transceiver devices if the transceivers are placed on a spherical surface [32, 44, 174]. By means of such spherical FSO devices, it becomes possible to achieve *angular diversity* via a spherical surface and *spatial reuse* via directional optical transmitters.

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. 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.

2.3.2 LOS Alignment and Multi-Element Designs with Electronic Steering

FSO communications is a promising complementary approach. It uses the unlicensed optical spectrum and most uses the same technology as the fiber optic communications. It can easily reach modulation speeds up to 10Gbps [25]. Its propagation medium is free space and does not necessitate costly fiber cable deployments. However, it cannot penetrate through walls and needs line of sight (LOS) alignment. In order for the FSO to become a complementary communication medium for mobile wireless access, the key problem to be solved is its vulnerability against mobility [38]. 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 the receiver must be aligned; and the alignment must be maintained to compensate for any sway or mobility in the nodes. Traditional solution approach to this problem of FSO communications has been to employ highly sensitive mechanical steering and tracking equipment with a powerful single transmitter such as a laser. The mechanical equipment physically rotates the transceiver to maintain the LOS alignment with the other device, which is also applying the same mechanical steering procedure. This approach can achieve establishing a wireless link even if the two communicating devices/nodes are moving with respect to each other. However, it produces device packages that are typically bulky in size, and thus, makes it very hard to develop portable FSO communication devices.

For outdoors, *fixed* FSO communication techniques have been studied to remedy small vibrations [143,144], swaying of the buildings have been implemented using mechanical auto-tracking [67,83,109] or beam steering [173], and interference [28] and noise [78]. LOS scanning, tracking and alignment have also been studied for years in satellite FSO communications [133, 154]. 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.

Recently, there has been some work on the beam coverage in FSO mobile network in order to overcome the misalignment problems caused by severe factors including vibration, motion and atmospheric turbulence by applying fiber-bundle approach to achieve continues beam coverage at the receiver without the application of mechanical equipments. The authors of [177] apply multiple fibers at the transmitter side with special lens to illuminate a larger area at the receiver side. Again, the focus has been on the transmission performance beam steering of the optical link to improve the performance when the misalignments takes place. Optical flow assignment has not been considered to manage multiple different data flows among transceivers during an ongoing transmission.

The idea of using multiple elements/transceivers in FSO communication has been used in interconnects [145], 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 Atmospheric Conditions

Free Space Optics has the potential to be future wireless communication technology with fiber-like bandwidth 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 communications techniques to mitigate turbulence-induced intensity fluctuations, i.e., signal fading [179]. They propose techniques in order to improve detection efficiency. They use the marginal 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 marginal statistics are known. To lead a further improvement in detection performance, they apply MLSD in situations where the temporal correlation of fading is known.

Chan *et al.* summarizes the current study and experiments in Free-Space-Optical communication which shows that free-space-optical communication is ready for operational usage [54]. However, he indicates that there are still improvements needed on the overall architecture to make the network efficient and reliable with focusing on cost performance improvements via innovations. Chan *et al.* focuses on three different attributes and suggests further improvement and redesign of the TCP protocol based on these three attributes. As a future research, he points out two different improvements in the current systems to reduce the cost. One potential improvement can be provided on the physical link communication efficiency by using photon-counting receivers. Second potential improvement can be provided with coherent systems in the clear-air turbulence.

Farid *et al.* considers the statistics of photo-electron count in pin photodiodes to measure the [84] 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 poison process in which the mean count is lognormal.

The authors of [112] 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.

2.5 Outdoor Ultraviolet FSO Communication

FSO communication has also been considered for ultraviolet (UV) communication at UV-C band. UV-C has also the advantage of full-duplex transmission at higher data rates with spatial reuse at the same time. Different from radio frequency (RF), the main issue in the UV-C communication is that the directionality and sensitivity to the line of sight (LOS). UV communication is mostly used for some ground sensing networks, military applications, landing control assistance and monitoring air molecules and particles. Recently, UV communication has also attracted some attention in the Free-Space-Optical communication field because of the recent and rapid developments on the UV devices. Authors tackles the recent developments on the

UV research experiments including UV devices, transceiver design and propagation models [171].

The directionality specifications and scattering effects of the UV communication is also considered for designing suitable network protocols at the MAC layer. The authors of [105] design a MAC protocol for outdoor communication in the UV-C band called UVOC-MAC to evaluate such effects caused by mobility, node density, number of directions, full duplex communication, tuning the pointing angle of the beam and collision probabilities. Authors present that UVOC-MAC differs from directional RF and proposed MAC protocols in directional RF by the nature of the physical carrier sense and spatial reuse possibilities are different in UVOC-MAC. By UVOC-MAC it is possible to exploit spatial reuse and there is an improvement on throughput up to 4 times compared to a MAC that does not exploit the environment properties.

UV communication is also considered for short range sensor networks as an alternative to RF for communication between distributed sensor in a wireless network with a focus of NLOS communication via scattered UV communication [152]. The communication range for such systems is between 1-2 km. The transmitted signal power drops off rapidly beyond the distance of 1-2 km. This technology is considered for tactical military applications where low power consumption is crucial for the entire system.

Although UV devices consume low power compared to infrared devices and has the advantage of less interference and PAT requirements, there is still a lot of work needed to improve efficiency and reliability in UV devices and products. In our study we considered IR spectrum and IR LEDs and IR Photo detectors due the availability of the off-the shelf components in IR communication market.

2.6 Visible vs. Infrared

The idea of using optical signals for wireless communication is not new. In fact, Bell proposed the idea of "photo-phone" and patented it in 1880 [41]. Photo-phone did not become a reality; however, free-space-optical communication (FSOC) has become a widely used wireless communication method by the introduction of infrared-based TV remote controllers. Infrared FSOC also quickly found applications in short distance communication between devices, especially portable ones. In 1993 the Infrared Data Association (IrDA) was formed to provide low-cost interoperable worldwide infrared technology and a forum to develop standards, which led the development of IrDA protocol. The field of FSOC attracted limited attention for long time compared to RF counterpart and found limited applications [40, 175] mainly due to mobility and line-of-sight (LOS) limitations. But infrared (IR) communication rejuvenated interest and use in short-range applications such as wireless digital links and local area networks. Like the other FSOC technologies, IR communication is not bandwidth limited and regulatory approval is not required. Since it uses direct detection technique in simple devices, it avoids the effects of multi-path fading.

IR communication, although useful for ultra-high speed performance, is not without its limitations. High frequency IR is harmful to the human eyes and therefore the usable bandwidth is limited. IR communication systems are not viable in turbulent atmospheric conditions, and are limited to short-distance or indoor use. Most terrestrial FSOC technologies (e.g., enterprise connectivity, last mile access network, and backup links) use IR frequency band due to eye safety issues. Most IR communication designs use LEDs as transmitters [22]. Compared to lasers, IR LEDs can be modulated at lower speeds (up to 155 Mbps) but they are cheap, small, low weight, consume low power, and have longer life times. IR FSO links can be implemented using IR laser light as well, but low-data-rate communication over short distances mostly employs LEDs. Maximum range for LED-based terrestrial links is in the order of 2 to 3km, but the stability and quality of the link is highly dependent on atmospheric factors such as rain, fog, dust, and heat.

An IR transmitter may have single or multiple sources (LEDs) directed via an optical element (lens) followed by a beam/pulse shaper and a filter for harmful radiation. The LED lasers emit in the near-infrared range of 780-950nm wavelength, with a power usually not exceeding 1mW [122]. Receivers in IR communication are usually in the form of an optical system, consisting of concentrator lenses, filters and highly sensitive photo detectors (PD), compatible with the range of the received wavelength. The main parameter to be considered while characterizing the optical receiver system is the field-of-view (FOV). This FOV angle is directly related to the collection area, i.e., the area the PD is able to cover. High collection area will result in a narrower FOV angle as expressed in the following equation [122]:

$$A_{coll} \sin^2(0.5FOV) \;\leq\; A_{det} \tag{2.1}$$

A_{coll} is the collection area (the normal area that covers the FOV), and A_{det} is the photo detector area. Hence there is a tradeoff between the achievable FOV and the actual collection area, since their product is limited by the photo detector area threshold.

2.6.1 Visible Light Communication

Lighting technologies are substitutes for sunlight in the visible spectral region (380-720nm) where sunlight is most concentrated and to which the human eye is the most sensitive. The history of lighting [49] can be viewed as the development of increasingly efficient technologies for creating visible light inside, but not wasted light outside, of that spectral region.

Developments in solid-state lighting devices, especially in white LEDs, in the last decade fueled the research expanding the usable spectral region from IR to visible and gave birth to new field of research called Visible Light Communication (VLC). VLC technology uses the light in the wavelength interval of 380-720nm emitted by white LEDs and offers several advantages over RF technologies [94]:

- Virtually unlimited bandwidth with over 350 THz range.
- Unregulated spectrum available for immediate utilization.
- Spatial confinement of the light beams provides inherent security eliminating interception or eavesdropping.
- Spatial confinement also allows spatial reuse allowing substantially improved throughput.
- Removal of (or reduced) multipath fading in intensity modulation which degrades the performance of unprotected RF links.
- High brightness white LEDs are becoming ubiquitously available for lighting applications due to their superior efficiencies over conventional lighting technologies and their cost is continuously decreasing.
- Potentially can be integrated with power line communication system which could eliminate the need for a separate data line to LED-based transceiver modules.

- Optical signals do not cause electromagnetic interference (EMI) which limits use of RF technologies at certain environments such as hospitals, airplanes, certain military settings etc.

- Visible (and infrared) light with limited intensity does not pose any health risk and therefore safe for most applications.

The use of IR LEDs for optical wireless communication was first proposed by Gfeller and Bapst [71]. However, using LEDs for VLC has recently got particular attention since the advantages of LEDs have drawn attraction to VLC research and development [15, 48, 101, 103, 110, 123]. The idea of fast switching of LEDs and the modulation of the visible light for communications was first proposed by Pang et al. in 1999 [130]. This was the first proposal in the context of intelligent transportation where VLC can be incorporated into traffic information systems as an information beacon for the transmission and broadcasting of information [30, 130]. However, the idea has immediately expanded to other application fields particularly indoor communication systems [95, 97, 129, 158]. VLC has gained prominence in conjunction with lighting and communication [124, 159]. The main focus has been to design a VLC system with white LEDs due to high lighting efficiency, environment compatibility, no out-of-visible-band advantage, better power efficiency and easy maintenance [62, 155, 169]. A lot of effort went into increasing the modulation capacity and achieving a transmission of long data range of commercial white LEDs [62, 66, 87, 121, 169].

In November 2003 the Visible Light Communications Consortium (VLCC) was established in Japan, having among its membership major Japanese industrial organizations including Toshiba, NEC, Panasonic, Sony, NTT DoCoMo. It was only in

2008 that the United States and Europe initiated and funded major research projects focusing on this technology. The European Union heavily funded the hOME Gigabit Access (OMEGA) project, seeking to develop global standards for home networking, including the use of optical wireless using infrared and VLC technology. In 2009, the IEEE issued a Call for Contributions on IEEE 802.15.7 VLC protocol, and held the first meeting. The IEEE 802.15.7 VLC Task Group is the official authority so far in this area. LVX Systems [24] have claimed to be able to commercially manufacture and deploy VLC systems. As a complement to Wi-Fi, the Li-Fi (Light-Fidelity) Consortium was formed in Oslo, Norway in 2011 [6]. Increased research produced remarkable results in the field including demonstration of multiple-input-multiple-output and integration to power line communication. [38, 62, 93] Despite the increased research efforts and noticeable demonstrations, the works reported in the literature focus on one aspect of VLC, typically communication, and ignore the other. Hence, there is need for a holistic approach in investigation of joint-design of hardware and software protocols considering needs and constraints of both illumination and communication aspects.

Apart from lighting and indoor wireless access points, VLC has been studied for other possibilities such as vehicular signaling and danger notification in traffic systems [161]. The growing use of LEDs in billboards, signs, and location instructions can be leveraged to provide information to nearby handheld devices. PureVLC, a UK based company has recently developed light messaging and *li-fire* VLC HD video transmission using smartphones and laptops [132]. As an effort to ameliorate growing environmental concerns, smart homes and smart lighting are gaining popularity all over the developed world. Smart houses, in addition to being zero carbon emission, have several automated capabilities, the most popular of which is assisted living for the elderly. Such smart houses have been built in Japan, Korea, Europe, USA, Australia and New Zealand [51]. VLC could play an important role in development of these smart homes by facilitating high-speed communication.

Compared to the traditional infrared communication, visible light communication can provide both illumination and data transmission. VLC systems have crucial advantages such as high emission power without hurting human eyes, no electromagnetic interference , no need to apply for spectrum resources, no optical data leak, and the lightning equipment is aesthetically pleasing [97]. Therefore, LED visible light communicating technology has a tremendous prospect.

2.7 Localization in MANETs

The problem of node localization has been studied in various contexts: using ranging techniques [73,85,163], bearing techniques [117], and their combinations of [34,55]. In this section, we position our work in the related literature that focuses on directional and energy-efficient methods for node localization.

2.7.1 Range-Only Techniques

Range-based methods require at least 3 nodes (4 in a 3 dimensional setting) with location information to enable localization of a fourth node with varying degrees of quality. The major limitation of range-only methods is that they require high density deployment of nodes to achieve high localization coverage. SpotON [85] and Calamari [163] systems build on the assumption of a simple path propagation model with known parameters for RF (via measuring the signal strength) whereas this does not hold in practical environments where multi path propagation is the norm, especially in in-door settings. Such systems have a 10% error in ranging even after an intense calibration process. Another ranging method is via measuring time-of-flight of an ultrasound or acoustic signal, which provide high accuracy in short ranges (a few meters).

The robotics and image processing communities have been working on the localization problem using landmark detection techniques and laser range finders [39, 98, 135]. However, those methodologies are irrelevant in MANET localization either because of power consumption concerns or lack of a camera.

Saravese *et al.* present an approach that is resilient to ranging errors in [146]. However, their list of constraints also confirm the fact that a high node density is required in order to achieve sound results of localization extent. Moreover, they propose a refinement phase based on confidence metrics that is employed after a node is able to triangulate. In such a refinement process, nodes that are closer to the anchor nodes have higher priority. This way of prioritization provided more insight in our research. We investigated different ways of prioritizing available localization information that is available from different nodes.

Whitehouse *et al.* presented Calamari which is their test bed for estimating the system parameters of an ad hoc localization system in [163]. Their design involves signal strength and acoustic time of flight measurement and extract the distance between two nodes using the difference between the speed of light and the speed of sound. The number of required message exchanges increase with the hop distance. The two main components in the system, i.e., radio transmitter and acoustic sensing device, although cheap and low-power-consuming, vary highly in accuracy. Hence, their work is mainly focused on eliminating accuracy problems.

2.7.2 Orientation-Only Techniques

Niculescu *et al.* argue that setting up infrastructures for localization only, such as beaconing mechanisms, would not be cost-effective for mobile systems in [117] and they consider angle of arrival detection devices such as an antenna array or a set of ultrasound devices to aid in both positioning and orientation. However, their simulations cover only static scenarios and their assumption is that the approach can be easily applied to *limited-mobile* systems. Their findings agree with ours as they indicate that localization errors are amplified as the number of hops from anchor nodes is increased and they try to avoid using ill-formed triangles while triangulation phase. Again, their usage of extra hardware is a disadvantage when compared with our approach.

2.7.3 Hybrid Techniques

Akella *et al.* proposed a hybrid technique in [34] that uses optical wireless (FSO) to further relax the requirement of node density to only one. The most important advantage of hybrid techniques is they do not require a high node density. Hence, they can achieve high localization extent without high messaging overhead or high node density. Although our work overlaps at the point that both approaches use FSO for its directionality, they need ranging measurements as well. Their work stands out to point that even 3D localization can be achieved without high node density.

Chintalapudi *et al.* lays out two highly desirable properties of ad hoc localization systems in [55]:

- unplanned placement of anchors since some environments may not permit precise placement of anchor nodes,

- ad hoc localization systems should be able to functions with good performance using an order of magnitude fewer anchors than nodes.

The second argument is an important way of distinguishing the family of localization schemes in terms of performance. Moreover, their conclusion of ranging-only techniques requiring node densities (an average of 11-12 immediate neighbors to achieve 90% localization with 5% accuracy) well beyond the density required for network connectivity implies that the bearing or sectoring techniques (i.e., techniques that require directionality) reduce this overwhelming requirement of node density significantly.

Even though the results that they present are promising and stand as a viable alternative to ranging only localization schemes, there is one shortcoming of their approach. It is unknown if accurate bearing (or even sectoring) estimation devices can be built at the form factors and energy levels of sensor networks. Our approach to the problem does not require an additional device and it uses the naturally available directionality information.

Akcan *et al.* present a GPS-free localization algorithm that can be used in mobile ad-hoc networks in [31] since GPS signals may not be available in enclosed environments. However, their assumptions and hardware requirements (compass and motion actuator) exceed the capabilities of a typical MANET node, especially when compared to our approach that does not require any additional hardware.

Langendoen *et al.* perform a fairly comprehensive comparison of three different localization algorithms: ad-hoc positioning, robust positioning and N-hop multileteration in [100]. They point out three common phases of distributed localization algorithms: determine node-anchor distances, compute node positions and iteratively refine the results. Their conclusion is that no, while no single algorithm outperforms the others significantly, there are cases where each may be preferable based on the requirements of the application.

Hightower *et al.* summarizes different approaches to the problem of node localization in [79]. From early solutions like proximity sensors [50, 99, 125, 131, 162] to scene analysis techniques [39, 98, 135] that are often employed in robotics community and to triangulation [7, 85, 98, 131, 135]. Their work contributes to classification and survey of available methodologies for localization. They also point out different concerns in the localization process such as privacy. The two basic approaches are: node itself calculating its own location using the information broadcast by external infrastructure and the infrastructure calculating a node's location and informing the node. Their work also contributes to proper justification of localization mechanisms since accuracy does not always increase linearly with the amount of cost. In the context of all the above literature on node localization, although our contribution to the solution of localization does not initiate a new branch, it certainly stands out because of the usage of intrinsically available directionality information without requiring any additional hardware.

Our proposition provides high localization extent with as little as only 2 GPS-enabled nodes with acceptable accuracy through the use of narrow transceivers when the 2-connectedness requirement is satisfied. Unlike the infrastructures used in [50, 131], the anchor nodes used in our simulations do not have extra communication or energy capabilities. Despite the conclusion of localization error being insensitive to the amount of anchor nodes in the network found in [100], our findings reveal that localization accuracy can be increased via denser deployment of GPS-enabled nodes which gives flexibility to post-deployment tuning. As flat (ill-formed) triangles were an issue for the lateration step in [116], we also watch for attempting to intersect parallel 3-D lines or collinearity and avoid the situation by not accepting the second information set that makes an angle less than a threshold value (e.g., 0.005*PI) with any of the previously accepted information sets. Also, we employ a similar sanity check that checks if the estimated location lies inside the line-of-sight of all of the transmitters. If not, we reject the estimate and fall back to the second best couple for a secondary estimation.

2.8 Transceiver/Channel Selection Mechanisms for Multi-transceiver Mobile Structures

FSO systems need high accuracy between the transmitter and receiver pairs in order to establish a reliable communication medium. The issue of building a reliable communication medium becomes more challenging when the mobility is also involved in an FSO scenario. Since the FSO transmitters are directional developing a reliable control system for data acquisition and tracking transceivers for establishing alignments on an FSO node is an urgent need. Tracking a mobile FSO receiver is mainly implemented considering beam steering mechanisms by adjusting beam divergence as an alternative to mechanical steering mechanism [178]. The need for a novel control system without expensive mechanical devices has always been under research.

In order for the FSO to become a complementary communication medium, a key problem to be solved is its vulnerability against mobility [38]. 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. Traditional solution approach to this problem has been to employ highly sensitive mechanical steering and tracking equipment with a powerful single transmitter such as a laser. The mechanical equipment physically rotates the transceiver to maintain the LOS alignment with the other device, which is also applying the same mechanical steering procedure. This approach can achieve establishing a wireless link even if the two communicating devices/nodes are moving with respect to each other. However, it produces device packages that are typically bulky in size, and thus, makes it very hard to develop portable FSO communication devices.

Since the mobility is the primary challenge for a reliable FSO system, maintaining LOS between different transceivers on a mobile FSO node becomes the focus of our study. Instead of mechanical steering over powerful and expensive FSO transmitters, we propose to devise "electronic steering" over multiple cheap transceivers such as LEDs. Our recent work showed that FSO mobile ad-hoc networks (FSO-MANETs) can be possible by means of such multi-transceiver devices if the transceivers are placed on a spherical surface [32,44,150,174]. By means of such spherical FSO devices It becomes possible to achieve *angular diversity* via a spherical surface and *spatial reuse* via directional optical transmitters. In this study, we propose a prototype of such a spherical FSO structure with multiple transceivers and evaluate 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 to show feasibility of maintaining optical wireless links over such multi-transceiver structures.

The key limitation of our study regarding transceiver selection is that the transceivers are active all the time meaning that power consumption issues are not considered. There are also hardware limitations on the current controller devices such that a limited number of transceivers can be activated at the same time. When the numbers of transceivers increase on the system, we need to manage the transceivers more efficiently compared to previous systems as the power consumption and hardware limitations were not a significant concern. Certain number of transceivers can be activated at a given time to track the alignments to establish a reliable communication between FSO nodes. When the nodes are mobile, activating certain number transceivers at a given time becomes a big challenge since the position of the nodes may change randomly. The challenge is that: which transceivers should be activated to track the alignments more efficiently on a spherical FSO structure. We will focus on different transceiver selection mechanisms in order to measure the throughput of the system in such scenarios.

There has been large body of work on 3-D tracking mechanism in different research fields considering particle filtering at 3-D spaces and sensory query mechanisms that has some overlap with the concept of our work. The authors of [102] formulate 3-D tracking problem with data fusion by extending 2-D bearing only tracking algorithm. The authors show that 3-D tracking can be done by applying multiple 2-D fusion. The authors of [176] use information driven sensor querying approach to track a moving vehicle through a two dimensional sensor field using Bayesian filtering decision methods. The authors of [59] presents two different techniques: information-driven sensor querying (IDSQ) and constrained anisotropic diffusion routing (CADR), for energy efficient data querying and routing in ad-hoc sensor networks. As a result, authors conclude that the information-driven sensor querying (IDSQ) and constrained anisotropic diffusion routing (CADR) approach are more energy efficient and tolerable to link failures. One possible problem in such techniques is the sensor selection can be redundancy in the information provided among available sensors in the network.

The challenge is to select an optimal subset and to decide on an optimal order of how to incorporate these sensors in the network. In such scenarios, the technique of the determining uncertainty is based on approximations by a Gaussian distribution model. Other methods can also be used to define the uncertainty and design a system accordingly as proposed in their paper to remedy the problem of selection strategy.

2.9 Summary

In this chapter, we provided the relevant literature work for FSO Communication and research efforts for its common use cases, problems and solutions related to FSO Communication. We covered several papers to serve the purpose, starting with a general introduction on bandwidth expectations of future applications. We concluded our chapter with the relevant literature on transceiver and channel selection mechanisms.

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 prototypes.

3.1 Basic FSO Transceiver Systems

A typical 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 as depicted in Figure 3.1. The transmitter performs as a modulated light source that transmits an optical signal, and a photo-detector at the receiving end reproduces the received optical signal and converts to an electrical signal. The medium in between the transmitter and the receiver attenuates or distorts the signal. Fiber-optic communication uses a guided medium known as ‘fiber’ to propagate the light to the receiver. Optical fibers can carry light signals across greater distances with less loss than metal wires and are immune to electromagnetic interference. Optical fiber has significantly lower attenuation compared to existing copper wire in long-distance high-speed applications. Fiber optic communication systems are widely used in the *wireline* telecommunications industry and have largely replaced copper wires due to their many advantages over electrical transmission, particularly due to the large capacity of the optical spectrum.

A special form of optical communication uses 'free space' as the transmission medium and is known as free-space-optical (FSO) (a.k.a. optical wireless) communication. As a *wireless* technology, FSO communication (FSOC) has recently attracted significant interest from telecommunication research and industry, mainly due to the increasing capacity crunch faced by the RF wireless technologies. Among other benefits, FSOC provides a much larger bandwidth but exhibits very different propagation and channel characteristics than the legacy RF systems.

There are many FSOC systems today which being used in numerous applications, including:

- complementary backhaul to existing wireless technologies [10, 72, 81]
- short-term wireless connection for information exchange between two portables, such as infrared links [22, 82]
- building-to-building connections for high speed network access or wide area networks [25]
- wireless input or control devices, such as remote controls and wireless game controllers [22, 26]

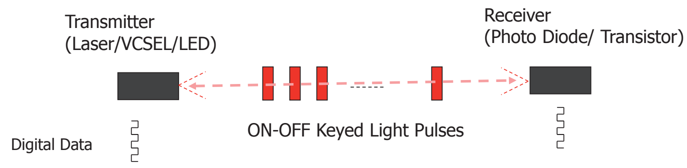


Figure 3.1: FSO Communication System

- wireless local area networks (WLANs) [10, 25, 111]

- communication between space crafts and satellite constellation [90, 153]

- inter- and intra-chip communication [172]

FSOC uses light propagating in free space to transmit data between two points. It is particularly useful where the physical connections by the means of fiber optic cables are impractical due to high costs or other considerations. FSO links can be implemented using laser light or with low data rates over shorter distances using light emitting diodes (LEDs). Maximum range for terrestrial FSO links is in the order of 2 to 3 kilometers, 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 range of FSOC is currently in the order of several thousand kilometers, but has the potential to bridge interplanetary distances of millions of kilometers, using telescopes as beam expanders.

The most commonly used components for FSO transmitters are laser diodes (LDs) and light emitting diodes (LEDs). Compared to LDs, LEDs are cheaper and they have longer lifetime. They can be modulated at high speeds but the optical power outputs are less than LDs. High optical output power of LDs poses potential risks for human eye and, therefore, prevents their indoor use. Laser beams may result in permanent blindness if a human retina is faced with a laser source because LDs

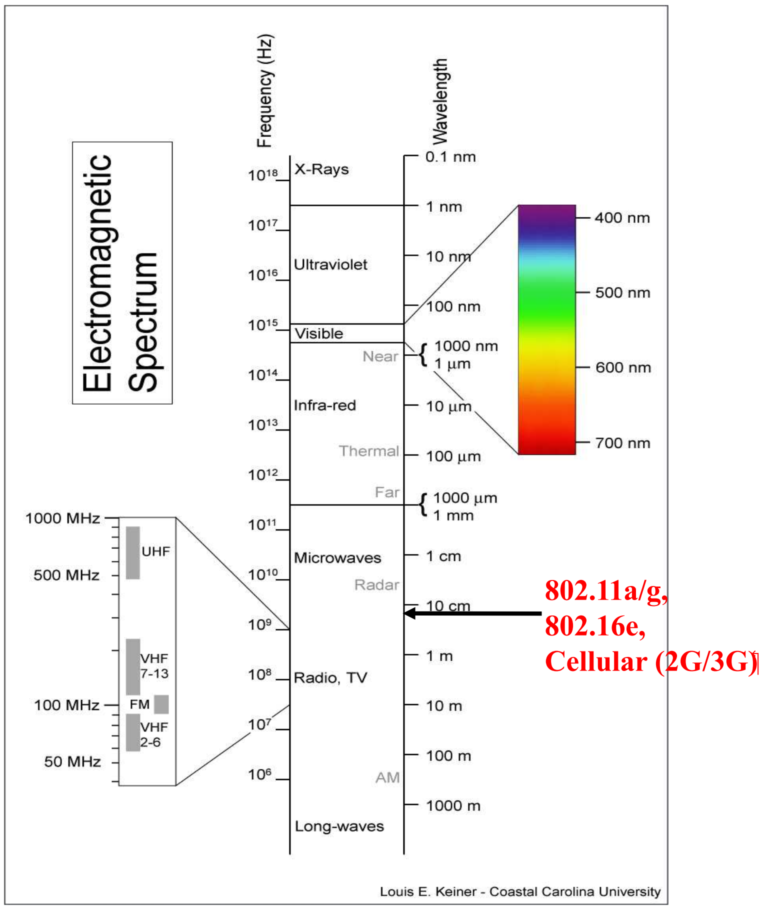


Figure 3.2: Electromagnetic spectrum usage.

are 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 directional as LDs and are safe at higher power compared to LDs. This is the key reason why LEDs are preferred for most indoor applications. Power consumption is also a big advantage for LEDs. Since LEDs consume much less power than lasers, they are preferred for most applications where power budget is a concern.

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 standards have been used to install over millions of low-cost, short range communication systems in laptops, handheld 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 inter-symbol 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 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 Prototypes

By employing commercially available off-the-shelf electronic components, we designed and built two different prototypes consisting of two main parts: Transceiver circuit and controller circuit. The transceiver circuit in the first prototype has a circular shape which includes both emitting diode and photodiode on itself, as shown in Figure 3.3. The controller circuit in the first prototype contains a microcontroller which is responsible for alignment detection, data transfer and data restoration. The controller circuit in the first prototype 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.

The core concept of the second prototype consists of a controller board and FSO transceivers attached to the controller board. The controller board consists of two parts, namely: (a) PIC32 Ethernet Starter Kit which is manufactured by Microchip Company [18] and provides Ethernet connectivity with TCP/IP stack software, and (b) an expansion board which allows user to fully access the MCU signals. FSO transceivers consist of an optoelectronic transmitter and receiver unit, which is capable of transmitting and receiving at the same time.

3.2.1 Proof-of-Concept Prototype

Transceiver Circuit

Transceiver circuit contains 2 LEDs, one photo-detector and a simple biasing circuit. Schematic of the circuit is shown in Figure 3.4 while picture of the front side and back side is shown in Figure 3.3. 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 [13] 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 [13] is used for receiving modulated signals. TSOP7000 is a miniaturized receiver for infrared remote control 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.

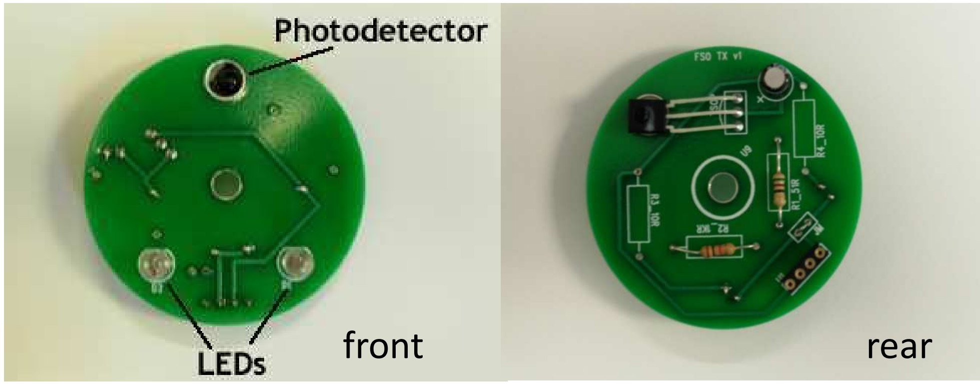


Figure 3.3: Transceiver circuit front and rear view.

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% .
- 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.

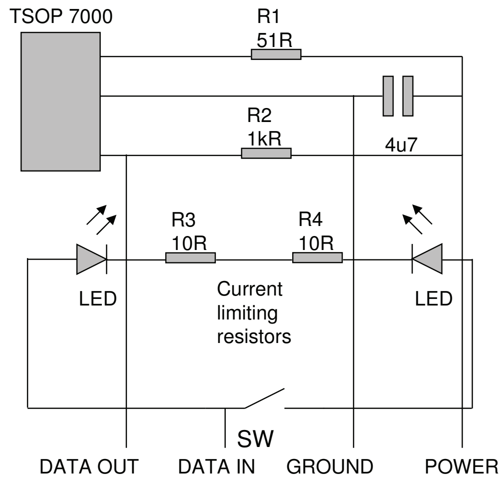


Figure 3.4: Transceiver circuit schematic.

Controller Circuit

Transmission units that carry the sent and received data are controlled by a microcontroller that runs the alignment protocol to decide whether an alignment is established or not. It also detects if an alignment goes down and it buffers data until the alignment is re-established. We used PIC24FJ128GA106 a 16 bit microcontroller [12] for implementing the alignment algorithm. The controller circuit shown in Figure 3.5 is responsible for searching for possible alignments and simultaneous data transmission through multiple transceivers.

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, mi-

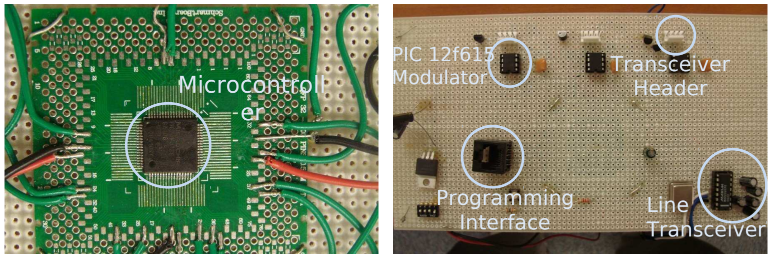


Figure 3.5: Picture of controller circuit.

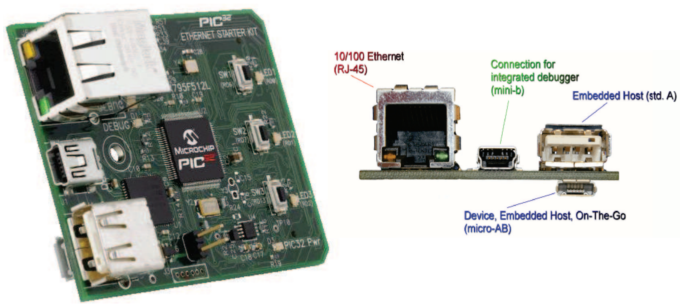


Figure 3.6: Picture of PIC32 Ethernet Starter Kit and starter kit connections [19]

crocontroller must have built-in serial ports. PIC24FJ128GA106 carries 4 built-in bidirectional serial ports onboard.

3.2.2 LOS Performance Measurement Prototype over a Voice File Transfer

This prototype is an improved prototype with faster transceivers. We show that it is possible to make voice file transfers and evaluate performance of these transfers over our LOS detection and alignment establishment protocol. Our prototype experiment includes varying transfer speeds and codec types. For simplicity, data rate that one node can reach at each transceiver will be up to 312500 bps. It is possible to receive and process multiple voice data streams simultaneously using the directionality of

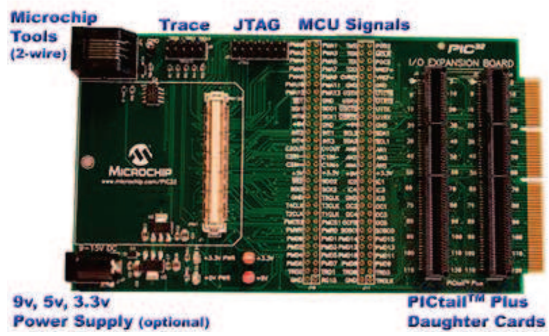


Figure 3.7: Picture of PIC32 Expansion Board [20]

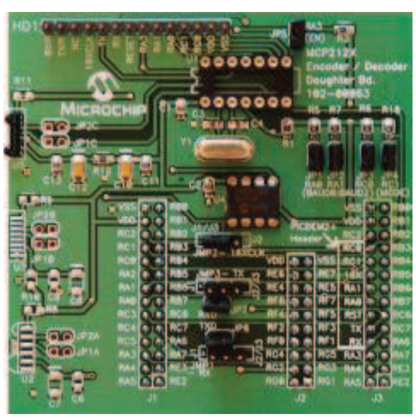


Figure 3.8: Picture of MCP212X Developer's Daughter Board [17]

FSO transceivers. With three different nodes , each node tries different voice file transfers among each other to evaluate the effects of the multi-transceiver design of the FSO structures and LOS alignment protocol on the quality of the voice by measuring the mean opinion score (MOS) of the transferred voice. We prove that disruptions below a reasonable threshold are recoverable in a seamless manner.

Figure 3.6 shows the second controller board used in our prototype. Again, the controller board is responsible for all operations to handle logical data streams and multiple transceiver connections. The prototype uses an LOS alignment protocol [150] which exchanges small frames with neighbor multi-element FSO nodes and identifies the transceivers that are in line-of-sight of each other. The LOS alignment protocol can be also considered as an enhancement with electronic steering on top of multi-transceiver FSO communication structures. The alignment protocol uses a simple three-way handshake messaging method for full assurance of bi-directional alignment between FSO nodes. Each frame header consists of 5 bytes. The first two bytes are used for marking the beginning of a frame. The third and fourth bytes include the sender and receiver information of the neighboring FSO nodes. The last byte is intended for determining the frame type, which also provides information about current alignment status when the nodes are exchanging alignment frames. In data frames, the sixth byte represents the length of the payload. Hence, the payload length is variable. When the frame type is not data, the protocol just exchanges 5 bytes of information in order to establish the alignment. The alignment algorithm requires exchange of only four frames. When the frame type is data, the payload length can be up to 100 bytes.

The PIC32 Ethernet Starter kit comes with TCP/IP stack implementation and it provides Ethernet connectivity. It contains PIC32MX795F512L, which is a 32-bit micro-controller. The PIC32MX795F512L micro-controller has six UART connections, but it is possible to use only up to three UART connections with the kit, since the remaining connections are used for the physical peripherals of the other components on the PIC32 Ethernet Starter Kit. The PIC32 Ethernet Starter Kit is capable of carrying out many Ethernet connectivity functions and can serve as a host computer connected to the network. The current protocols supported by TCP/IP stack are ARP, IP, ICMP, UDP, TCP, DHCP, SNMP, HTTP, FTP and TFTP. In this prototype, we used a cross-layer design where the alignment protocol works directly with the TCP/IP stack software. Although limiting performance of our prototype, our choice of cross-layer design aims to benefit from the flexibility of working with TCP/IP protocols.

In order to access the pins of the starter kit, we used an expansion board that is developed by the Microchip Company [18]. The expansion board provides easy access to starter kit control I/O pins. Figure 3.7 shows the picture of the PIC32 Starter Kit expansion board and I/O maps of the expansion board.

One aim of the prototype is also to show that an FSO system can be built by only using off-the-shelf components. We used MCP212X Developer's Daughter Board for the transceivers. The board includes an infrared encoder/decoder and an infrared transceiver module that is capable of communicating at 312,500 bps. The transceiver module includes a PIN photodiode, an infrared emitter (IRED), and a low-power control IC. Extended IrDA provides 1 m as low power range, which can be adjusted to shorter ranges via external current control resistor. The infrared encoder/decoder integrated circuit (IC) can also be used for custom designs. We used MCP2120 infrared encoder/decoder, which encodes an asynchronous serial data stream, converting each data bit to infrared signal. At the receiving side, the message

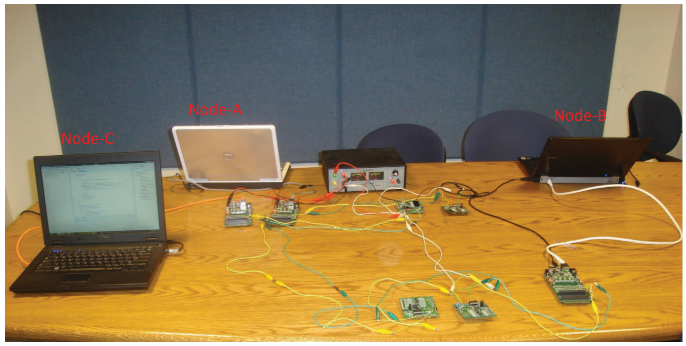


Figure 3.9: Prototype Setup: Three nodes, Node-A sends file to both Node-B and Node-C

is encoded to UART formatted serial data.

The experimental setup consists of three laptop computers, 3 PIC32 Ethernet Starter Kits with PIC32 starter kit expansion boards, and 4 MCP212X Developer's Daughter Board. Each PIC32 Starter Kit is connected to a laptop computer via Ethernet port and the starter kit provides one host connectivity to a computer. Thus, it serves as a server to a client computer. MCP212X Developer's Daughter Boards are connected to the UART ports of the PIC32 Ethernet Starter Kits. Figure 3.9 shows the current setup. Laptop computers communicate with the starter kits using TCP connection over Ethernet, and the starter kits on each node communicate using infrared transceivers on UART ports.

3.3 LOS Alignment Protocol for Electronic Steering and Localization Algorithm

3.3.1 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 automatic hand-off of data flows among different transceivers while achieving a virtually omni-directional propagation and spatial reuse at the same time [174].

The main purpose of the alignment protocol is to make alignment process seamless to the higher layers of the protocol stack. Figure 3.10 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 3.10.

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 3.11). 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

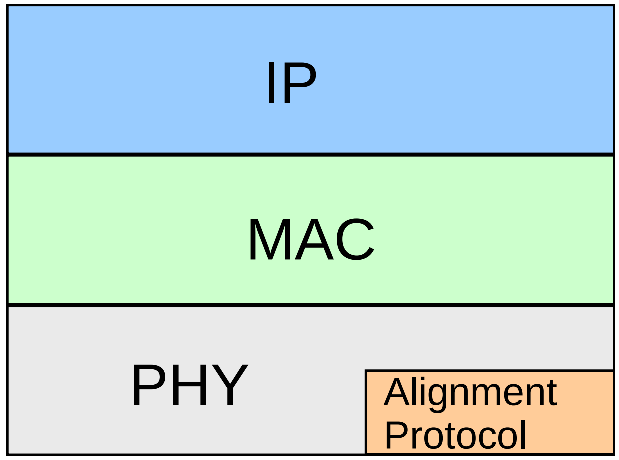


Figure 3.10: Default placement of alignment protocol in protocol stack.

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 four different types of frames. SYN, SYN_ACK, ACK and DATA. Re-alignment algorithm starts by sending SYN frames through a particular transceiver (let's 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.

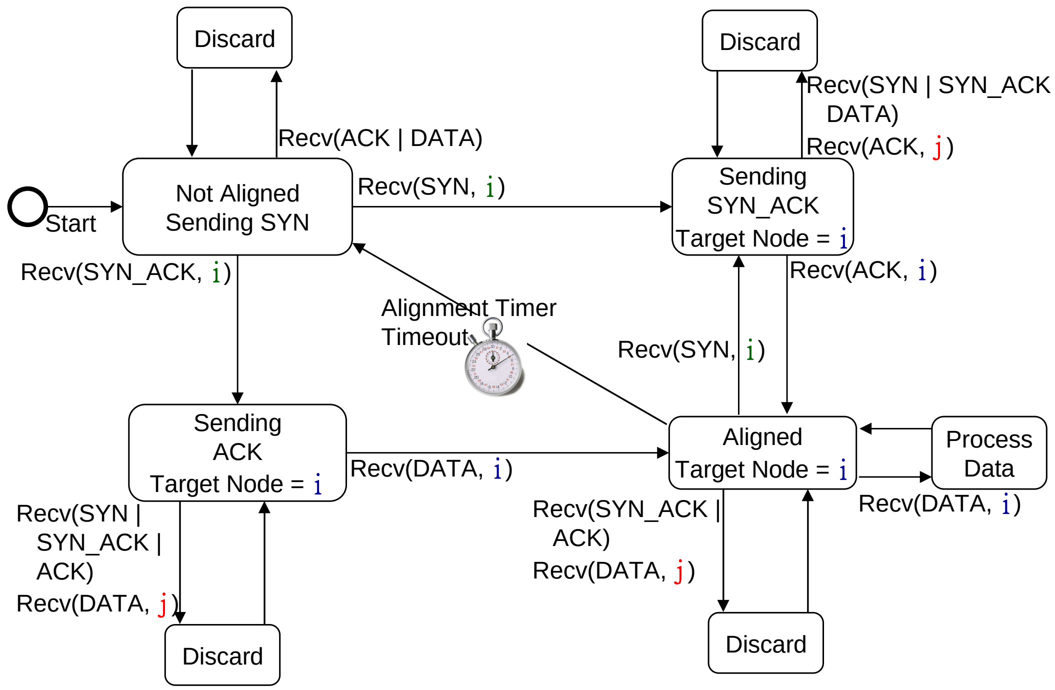


Figure 3.11: State diagram of alignment algorithm.

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 as shown in Figure 3.10. 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.

3.3.2 Localization Algorithm

FSO communication is prone to mobility and it requires establishment and maintenance of line-of-sight (LOS) between FSO transmitters since FSO transceivers are highly directional. The LOS detection and establishment protocol handles this problem and makes it possible to send localization packets to the appropriate transceiver on our prototype. This shows that we can also use the prototype for an FSO based localization technique. In order to achieve localization we made some modifications to our transceiver circuit. We used different types of LEDs from different manufacturers in order to make measurements and alignment more reliable. Most of the LEDs that we use are GaA1As double heterojunction LEDs with varying peak emission wavelengths of 850 to 950 nm. We observed that most of the infrared LEDs' signals reflect from walls in an indoor environment which makes measurements unreliable and difficult. We tried to find LEDs with very narrow divergence angle in order to make more sensitive measurements of angle-of-arrival. We measured each LED's divergence angle by using our transceiver circuit, since the conditions in which the measurements are done to gather these LEDs' specifications by manufacturers may be different than our lab conditions. So, we measured the divergence angle of each LED with our transceiver circuit also considering reflections in our indoor environment. Among 12 different LEDs we selected SFH 4881 [27], which is reliable and has a fabricated liquid phase epitaxial process. The angle of half intensity is stated ± 5 in the data sheet and in our experiments we measured the angle of half intensity of SFH 4881 at about ± 16. This was the most reliable and stable LED in our lab experiments.

Algorithm 1 Alignment Algorithm

```
DEFINE FRAME TRANSMIT TIMER HANDLER ROUTINE:
UPON Time to transmit a frame:
for all Interfaces of the node do
    if The interface is in SENDING_SYN state then
        SEND OUT SYN FRAME
    end if
    if The interface is in SENDING_SYN_ACK state then
        SEND OUT SYN_ACK FRAME
    end if
    if The interface is in SENDING_ACK state then
        SEND OUT ACK FRAME
    end if
    if The interface is in ALIGNED state then
        FIND a DATA Frame That Has a Next Hop That is Same With the Aligned Node
        SEND OUT DATA FRAME
    end if
end for
FRAME RECEPTION FROM A TXC HANDLER ROUTINE:
UPON The Event Of Reception of a Frame: PROCESS PROTOCOL FRAME
if Received Frame is a DATA Frame then
    RELAY Frame to Host Computer
end if
FRAME RECEPTION FROM HOST COMPUTER HANDLER ROUTINE:
UPON The Event Of Reception of a Frame:
BUFFER Frame Temporarily
PROCESS PROTOCOL FRAME ROUTINE:
UPON The Event Of Reception of a Frame:
if The interface is in SENDING_SYN state then
    if Received Frame is a SYN Frame then
        UPDATE State as SENDING_SYN_ACK
    end if
    if Received Frame is a SYN_ACK Frame then
        UPDATE State as SENDING_ACK
    end if
end if
if The interface is in SENDING_SYN_ACK state then
    if Received Frame is a SYN_ACK Frame AND Received From the Same Node then
```

Algorithm 2 Alignment Algorithm (cnt.)

```
        end if
        UPDATE State as SENDING_ACK
        if Received Frame is a ACK Frame AND Received From the Same Node then
            UPDATE State as SENDING_DATA
        end if
    end if
    if The interface is in SENDING_ACK state then
        if Received Frame is a SYN_ACK Frame AND Received From the Same Node
    then
            UPDATE State as SENDING _DATA
        end if
        if Received Frame is a DATA Frame AND Received From the Same Node
    then
            UPDATE State as SENDING_DATA
        end if
        if Received Frame is a SYN Frame then
            UPDATE State as SENDING_SYN_ACK
        end if
    end if
    if The interface is in SENDING_DATA state then
        if Received Frame is a SYN Frame then
            UPDATE State as SENDING_SYN_ACK
        end if
    end if
```

In a frame of type DATA, the fifth byte is the length of the payload. Hence, the payload length is variable. On a localization packet the payload length is 6. First three bytes are the coordinates of the X, Y, and Z location of the node that is sending the localization packet. The second three bytes are the normal values of the corresponding transceiver that is sending the localization packet. If a node receives two different localization packets from different nodes, it calculates the location information using Closest-Point-Of-Approach Of The 2 Rays approach [4].

SFH4881 consumes low power. The maximum ratings for the forward current is 200 mA according to its specifications [27]. The power consumption of the LED is approximately 15mW when it is derived with a forward current of 100mA. We measured the forward current as 13mA and the forward voltage as 1.2 V for our prototype. The power consumption of one LED is approximately 1.56 mW. It is possible to use different LEDs with less power consumption to optimize the prototype for a power critical scenario. In this thesis, since our focus is prototyping the localization algorithm, we have not optimized the prototype design for power consumption. It is an interesting future work direction to explore the trade-offs in designing multi-transceiver FSO structures with minimal power consumption.

3.4 Summary

In this chapter, we introduced the basic building blocks of a typical optical communication system and their usage in the real world along with different examples. We presented the details of our prototypes and capabilities of these prototypes for different use cases. We delved in to the details of our LOS Alignment Protocol and showed the placement of LOS Alignment Protocol in the protocol stack.

Chapter 4

Optical Wireless Localization

In this chapter, we explore the possibility of using directionality of free-space-optical (a.k.a. optical wireless) communications for solving the 3-D localization problem in ad-hoc networking environments. Range-based localization methods either require a higher node density (i.e., at least three other localized neighbors must exist) than required for assuring connectedness or a high-accuracy power-intensive ranging device such as a sonar or laser range finder which exceeds the form factor and power capabilities of a typical ad-hoc node. Our approach exploits the readily available directionality information provided by a physical layer using *optical wireless* and uses a limited number of GPS-enabled nodes, requiring a very low node density (2-connectedness, independent of the dimension of space) and no ranging technique. We investigate the extent and accuracy of localization with respect to varying node designs (e.g., increased number of transceivers with better directionality) and density of GPS-enabled and ordinary nodes as well as messaging overhead per re-localization. Although denser deployments are desirable for higher accuracy, our method still works well with sparse networks with little message overhead and small number of anchor nodes (as little as

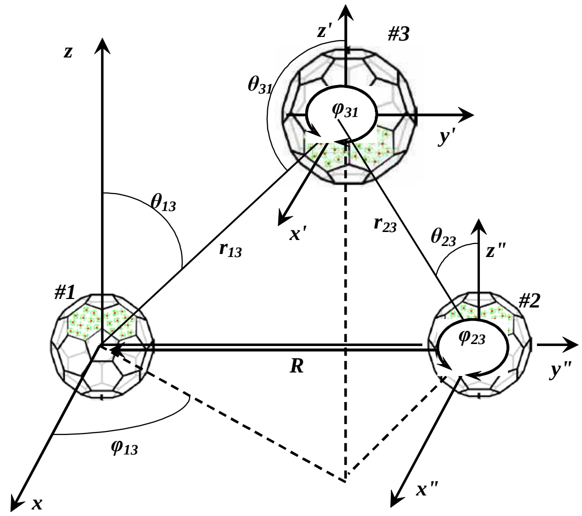


Figure 4.1: A third node triangulating using the advertised normals received from two other localized or GPS-enabled nodes.

2). We conduct simulations in NS-2 environment and present results. In Chapter 5, we also present a proof-of-concept prototype of our FSO-based localization techniques and show the validity of our approach even with three transceivers per node.

Providing contextual location information for the application-level data is a vital enhancement for ad-hoc networks. Localization capabilities are also important for network-level functionalities such as routing. Geographical routing protocols such as GPSR [91] are known to reduce the forwarding table sizes substantially, however, they need to know the location of nodes to do a successful ID-to-location mapping. Despite the strong need for localization, the task of localizing an ad-hoc node given its power capabilities, mobility, and other network parameters (e.g., node density, anchor density) is not trivial. Traditional approach of sensing the signal strength from 3 neighbors and triangulating using the derived distances requires a high neighbor density (3 localized neighbors) and is not accurate due to the multi-path loss in RF propagation. The issue becomes even more severe if the problem is considered in 3-D space, since then, it takes 4 nodes (reaching up to 2 times the normal node density) to

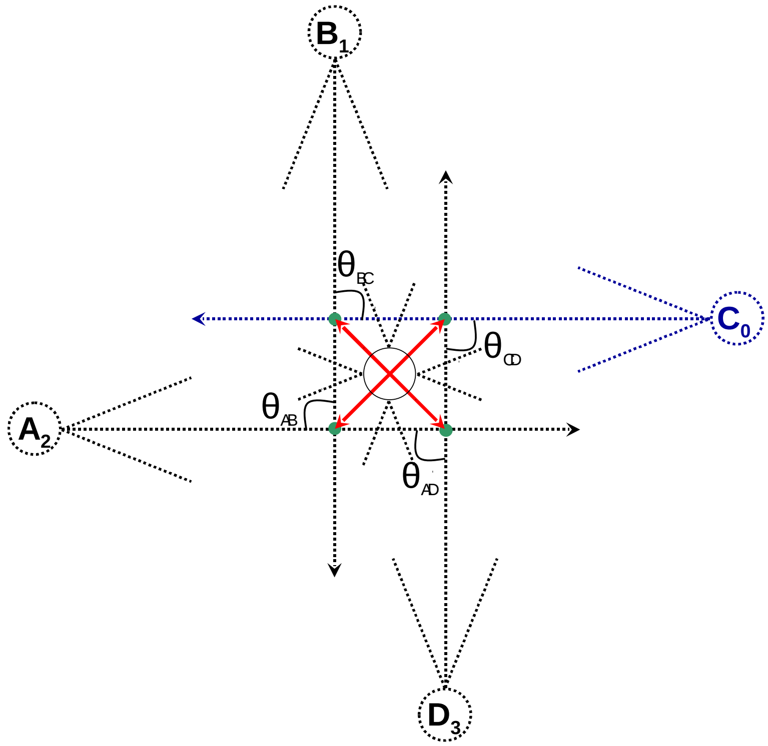


Figure 4.2: A simplified triangulation in 2D using two GPS-enabled nodes and error in default LOS model.

triangulate and even more samples (preferably from different neighbors) for calibration and better accuracy [55]. Sonar and laser range finder devices are not suitable for the power capabilities and form factors of ad-hoc nodes and explicit bearing devices are space consuming. Alternatively, we propose to use the *directionality that is inherent in FSO communication* which does not impose any additional hardware requirements. In our approach, a node can calculate its location given that it has 2 neighbors that know their own location, and advertise their location and interface normals in the packets that they transmit. Our method is lightweight in comparison to range-based methods since it *only requires 2 localized neighbors* and it *does not involve a complex tuning phase.*

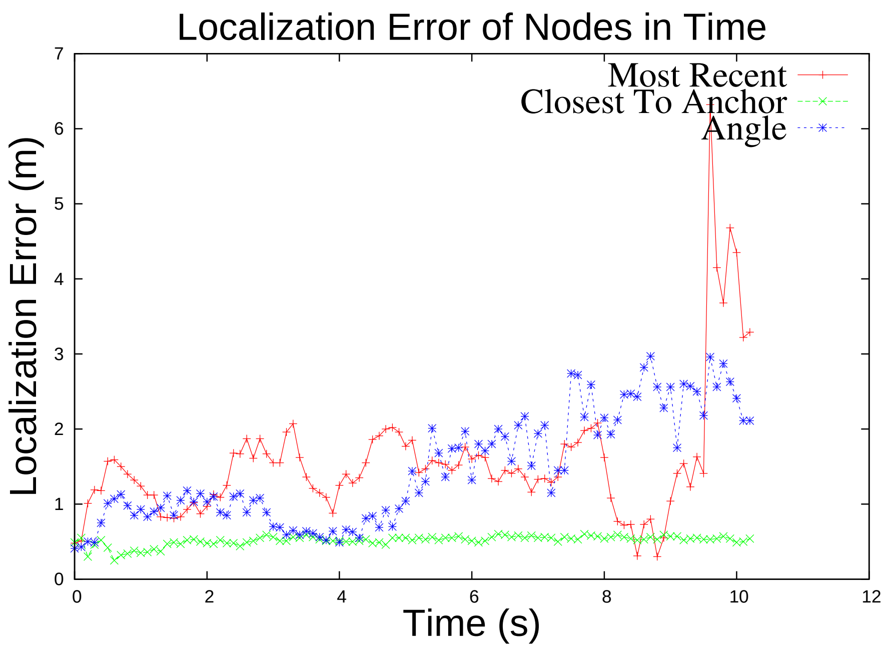


Figure 4.3: Localization errors are being amplified during the simulation when two latest received information sets are used for triangulation.

We considered FSO as a complementary communication mechanism to aid in increasing the overall network throughput in [44]. Previous studies revealed that FSO-only mobile ad hoc networks are viable and using *auto-alignment* circuitry and protocol, line-of-sight issues can be remedied significantly [107,108,150,174]. However, FSO communication technologies has not been used to solve the ad-hoc localization problem and they provide a substantial amount of potential as it is quite efficient to run triangulation algorithms using *direction of reception* (i.e., angle of arrival). We use directionality of FSO beams to identify the angle of arrival (Figure 4.1). By using *advertised normals* in packet headers, we can then calculate the relative angular orientation of neighbors with respect to each other. Since a node can receive packets (with advertised normal information in them) from more than 2 neighbors, we need to choose which information sets to use while triangulating. We suggest and compare three different heuristics to make this selection.

Key characteristics of our FSO-based solution are:

- capability of localization in 3-D,
- much less power consumption in comparison to techniques requiring RF hardware,
- only two localized neighbors are needed, which reduces the node density requirements, and
- fast heuristics to select a subset of neighbors to use for localization.

Besides these three different heuristics, we also provide a proof-of-concept prototype implementation for a basic FSO-based localization scenario. In this scenario, we used three nodes (two stationary and one mobile) each with three FSO transceivers, and showed that a mobile third node can localize itself by exchanging FSO-based messages with the other two stationary nodes even though it is moved to 7 different locations on an arc of a semi circle with varying diameter values.

A key characteristic of our solution is to use *optical-only techniques* to achieve localization. Our method requires much less power availability than RF-based methods, and is particularly useful for ad hoc networking settings where line-of-sight exists among low-power nodes. Our proposition provides high localization extent with as little as only 2 localized or GPS-enabled nodes with acceptable accuracy through the use of narrow transceivers when 2-connectedness requirement is satisfied.

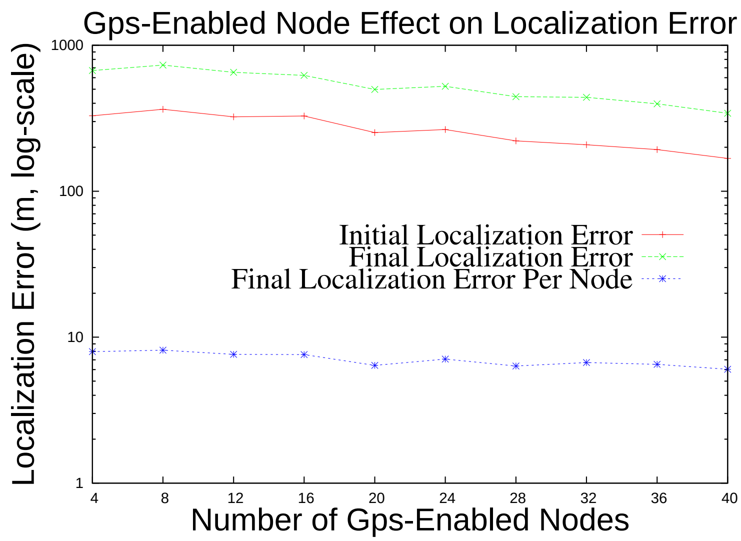


Figure 4.4: GPS-enabled node effect on localization error.

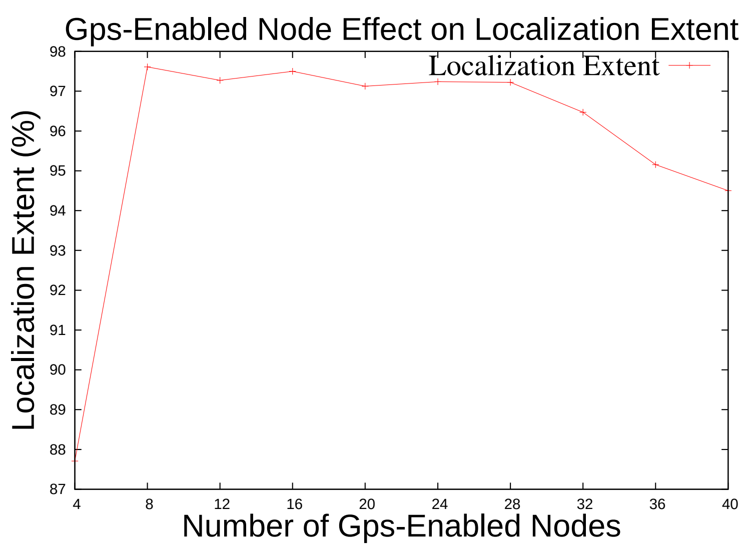


Figure 4.5: GPS-enabled node effect on localization extent.

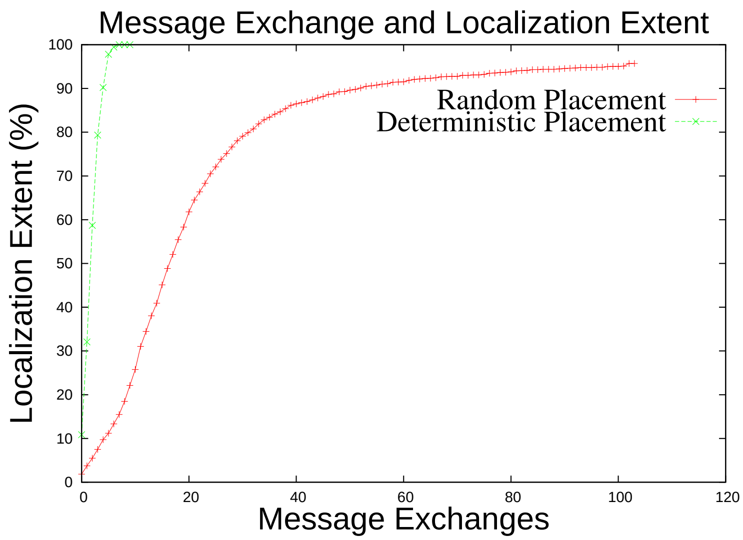


Figure 4.6: Localization extent with respect to message exchange for 200 nodes.

Algorithm 3 Relative Localization

```
UPON Reception Of Packets With Localization Header:
if This Node Has At Least 2 Neighbors' Advertised Normals AND It Is Not A GPS-Enabled Node then
    Determine Which 2 Localization Information Sets To Use Via One Of The Heuristics
    if Using Most Recent Sets To Triangulate then
        FIND 2 Latest Received Localization Packets
    end if
    if Using Angular Priority then
        FIND 2 Localization Packets That Make An Angle Closest To 90°
    end if
    if Using Localization Rank then
        FIND 2 Localization Packets With Minimum Ranks
    end if
    CALCULATE Closest-Point-Of-Approach Of The 2 Rays
    UPDATE This Node's Location
    UPDATE This Node's Localization Rank
    UPDATE This Node's State Flag As "Triangulated"
    START Stamping Outgoing Packets
end if
```

4.1 System Model

The 2 types of nodes are: anchor nodes with GPS devices and ordinary nodes that do not know their locations initially. Network nodes with a GPS device send control packets including their location and direction information so that the immediate neighbors without a GPS device can use the transferred information to find their own locations. These control packets convey the *advertised normals*, which include sender node's ID, if sender has a GPS device, if sender has previously triangulated, hop distance of sender from the nearest anchor node (localization rank), if the sender node has previously triangulated, and transmit antenna's global location and its direction (normal). The receiver of such a packet stores this information in a table (mapping from node ID to localization information) with the arrival time of the packet as presented in Algorithm 1.

One can derive simple algebraic equations:

$$r_{31} = \frac{R}{\sin\theta_{31}(\tan\varphi_{31} + \tan\varphi_{32})}\sqrt{1+\tan^2\varphi_{31}} \tag{4.1}$$

$$r_{32} = \frac{R}{\sin\theta_{32}(\tan\varphi_{31} + \tan\varphi_{32})}\sqrt{1+\tan^2\varphi_{32}} \tag{4.2}$$

$$X_3 = X_1 + r_{13}\sin\theta_{13}\cos\varphi_{13}$$

$$Y_3 = Y_1 + r_{13}\sin\theta_{13}\sin\varphi_{13}$$

$$Z_3 = Z_1 + r_{13}\cos\theta_{13} \tag{4.3}$$

that give the location of a third node. The distance between two GPS-enabled nodes is R (Nodes 1 and 2). From this distance and θ and φ angles that are derived from the transmitter normal advertisements in packet headers, we can calculate r_{31} and r_{32} (Equations 4.1 and 4.2). Lastly, we need to conduct simple vector additions to find the coordinates of Node 1.

Localization rank of a node is the hop distance of that node from the nearest anchor node. As depicted in Figure 4, node C has rank 0 indicated as a subscript. When a node without a GPS device triangulates, it's rank is the maximum of the ranks of sender nodes added by 1. Hence if a node is next to 2 GPS-enabled nodes (each with rank 0) and it triangulates using the information that it received from these two nodes, it will have rank 1. Such a ranking mechanism helps us prioritize the available information while triangulating. Intuitively, if we consider a network with uniform geographical distribution of nodes and anchor nodes placed at the center, nodes that are in the skirt of the network will have the highest ranks. Moreover, nodes with higher ranks are subject to larger localization errors.

A node is"ill-connected" when the number of directly reachable neighbors is less than 2. Hence, we require a node to be in transmission proximity of at least 2 direct neighbors even though it may not be able to transmit and receive from those neighbors because of line-of-sight issues. Thus, upon starting to place ordinary nodes (without GPS devices), we place the anchor nodes at arbitrary locations. For example, if number of GPS-enabled nodes in X axis is 2 and in Y axis is 3, we divide the X edge of the determined area into 3 and Y edge into 4 equal lengths and place one anchor node at the end of each X-Y edge with another corresponding anchor node placed on the same point with a given Z value. Hence a pair of GPS-enabled nodes are placed on top of each other with some distance in Z axis. We acknowledge that such a requirement on the placement of anchor nodes can limit the applicability of our approach. However, one can come up with placement methodologies that relax such strict placement requirements and ensure that a subset of surrounding non-anchor nodes have 2 connections to separate GPS-enabled nodes.

While placing non-anchor nodes, we consider a candidate location drawn from 3 uniform randoms for X, Y, and Z coordinates. We check if there are at least 2 nodes within the communication range of the candidate location. If so, we accept the candidate location and move to the next node. If we assume that there is only one pair of GPS-enabled nodes in the network, rest of the nodes form a sphere-like cluster in 3-D space. Moreover, when we increase the number of GPS-enabled node pairs to 2, we introduce the possibility of creating two disconnected clusters and enable the nodes to be placed in a larger volume, which in turn may decrease localization extent in the network because of line-of-sight issues involved. The only strict requirement while placing anchor nodes is that they are *placed as pairs*, on top of each other, which ensures that a third node that is able to see both nodes can localize itself.

4.2 Heuristics

In our study, we found that it is possible to employ a number of *simple heuristics* while deciding which two information sets to use for triangulation from a given number of information sets. Possible number of different ways to localize is $\binom{n}{2}$ where n is the number of information sets available to a given node.

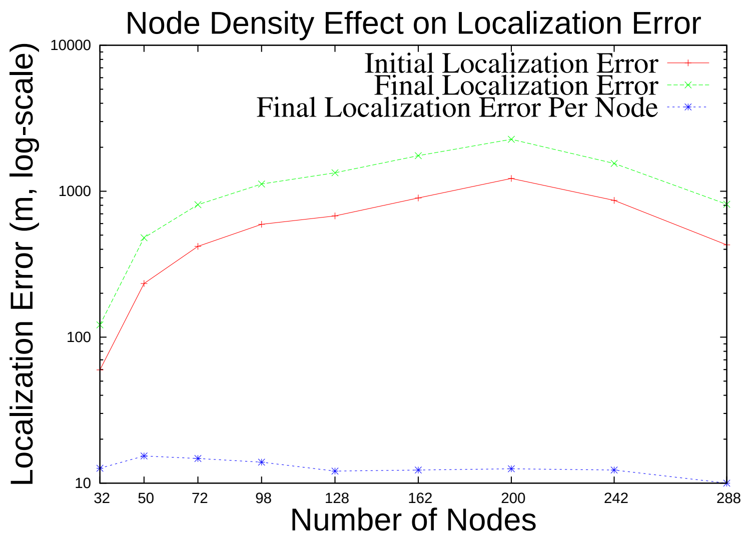


Figure 4.7: Node density effect on localization error.

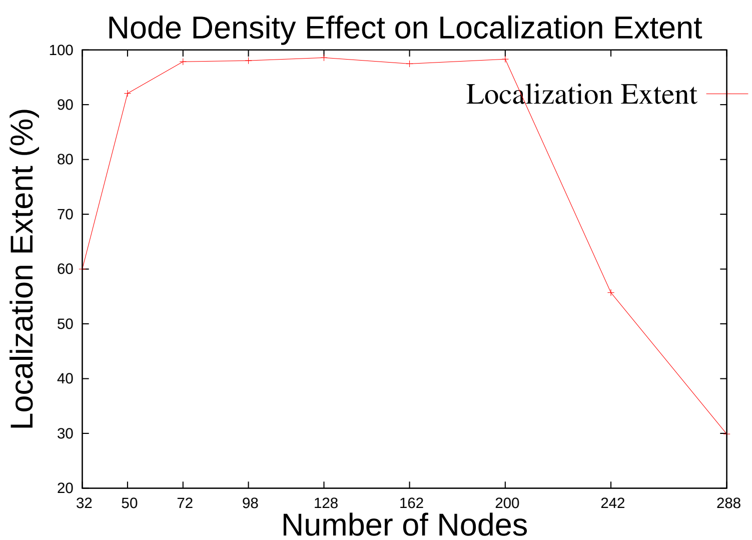


Figure 4.8: Node density effect on localization extent.

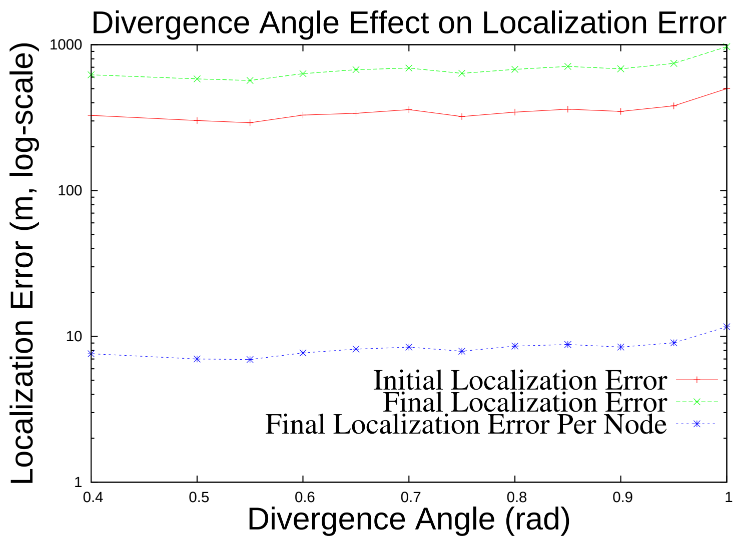


Figure 4.9: Divergence angle effect.

4.2.1 Stale Info Gets Forgotten

Possibly the simplest heuristic is to use the information that became available the latest. Assuming a node can use 4 different localization information sets as depicted in Figure 4, the triangulating node will select the latest two arrivals. Observe that localization error is amplified throughout the network with this heuristic. Since each node re-triangulates as it receives a packet using the most up-to-date information, node will consider the latest information no matter how far the sender node is to the closest anchor. Hence, even though more accurate information is available, the choice results in increased localization errors as can be seen in Figure 4. We found that the best triangulation result is obtained at the first attempt since the received localization information sets have been propagating from anchor nodes towards the nodes with higher ranks at skirts of the network.

4.2.2 Lower the Rank the Better

In this heuristic, we first assign a "localization rank" of 0 to a GPS-enabled node. When a node triangulates using localization information obtained from two neighbors, it attains the localization rank of maximum of the two neighbors added by 1. If we assume that the network has only one pair of GPS-enabled nodes and the distribution of the nodes form a sphere-like shape in 3-D, nodes that are closer to the core where the two anchor nodes reside, will have lower localization ranks and the outer skirts of the network will have larger localization ranks indicating that they are more distant from the core in number of hops. Hence, when a node is about to decide the pair of neighbors for triangulation, it may choose them in such a way that summation of the two ranks is minimized. This heuristic ensures that neighbors that are closest to anchor nodes are selected for triangulation. Figure 4 shows nodes' ranks as subscripts. Assuming the node in the middle is triangulating, it will select the information sets that came from C_0 and B_1 since they have the lowest ranks.

4.2.3 Angular Prioritization

One of the hard cases to triangulate using only directionality information is when the triangulating node lies on the straight line that passes through the both two nodes (collinearity). Results become more accurate when the two nodes are chosen in such a way that they attain a certain angle between each other (e.g., 90°). Throughout our experiments we found that one major factor that was causing increased localization error was ill-formed (flat) triangles that were the result of unwisely chosen 2 candidate information sets. A natural way to remedy the problem is to impose a lower bound on the angle between the two nodes (e.g., $0.005 * \pi$) and favor those sets making an angle close to 90° (orthogonality, in 3-D). Figure 4 shows θ_{BC}, θ_{AB}, θ_{AD} and θ_{AD} angles made by all 4 nodes. Assuming θ_{BC} is closest to 90°, the triangulating node will choose information sets sent by node B and node C for triangulation.

4.3 Performance Evaluation

We looked at a number of metrics while justifying the performance of our approach. The first metric is initial localization error. Initial localization error indicates the *aggregate absolute difference* between calculated location and actual location of all nodes in the network. This metric is calculated for a node when it localizes itself for the first time. Nodes in the network continue to re-localize themselves as they receive more packets. We stop the simulation when all the nodes are localized or simulation time reaches 10 seconds, whichever happens first. Since the simulated network is stationary, 10 seconds is enough as an upper bound for simulation duration. We calculate final localization error using the last calculated locations of each triangulated node before the simulation ends because of either of the reasons. Another metric that needs to be considered is final localization error averaged by the number of all localized nodes.

4.3.1 Comparison of Heuristics

We ran simulations of 100 nodes with 14 interfaces on each for 10 iterations using each heuristic. Each interface had a divergence angle of 600 mrad (~34°). There were 8 GPS-enabled nodes (making 4 pairs) and all nodes were placed on the 3-D volume randomly. We found that selecting the latest information set gives the worst results since the error is neither predictable nor close to a desired level. Similarly, angular prioritization gives elevated localization errors as well but still better than selecting the latest information sets and is relatively stable. Among the 3 heuristics, the one based on localization ranking resulted the lowest localization error per-node as depicted in Figure 4. Hence, throughout the rest of the simulation sets, we used this ranking based heuristic to determine which 2 sets to use for triangulation.

4.3.2 Node Density

Our second simulation set is designed to determine the effect of node density in the network on localization extent. For this experiment we increased the number of nodes from 32 to 288. There are 26 interfaces with 400 mrad of divergence angle on each node. There are 16 anchor nodes in the network and all of the ordinary nodes are placed randomly on a 3-D terrain. We ran the simulation setup for 5 iterations and averaged the results. As depicted in Figure 4.1, we found that as we increase the node density, the localization extent first gets higher, but later reduces as more neighbors start falling into their blind regions (i.e., no line-of-sight) and start becoming obstacles to each other. A similar trend is observed in localization error (Figure 4.1) as well. However, the final per-node localization error steadily benefits from more neighbors.

4.3.3 Anchor Density

In Figure 4 and Figure 4, one can see that in a simulation of 100 nodes, when the number of GPS-enabled nodes is increased from 4 to 40, both *aggregate* and *per-node* localization errors decrease. Also, it is an important observation that the localization extent makes a significant jump from 2 pairs (4 nodes) to 4 pairs. However, increases after that point reduce the localization extent. We conclude that because of the scattering effect of the random node placement algorithm, the volume that the nodes are distributed is increased, which in turn makes the LOS a more significant problem.

4.3.4 Divergence Angle

Figure 4.1 shows the how divergence angle affects the overall and per-node localization error. As we increase the divergence angle, it reduces the accuracy of the default-normal estimates. Hence, the localization error is increased. Designing multi-element optical antennas with more transceivers on them not only increases throughput [44], but it also increases the accuracy of localization.

4.3.5 Message Overhead and Localization Extent

A key practical metric is how long it takes the whole network to localize. In this set of simulations, we investigated the localization extent after each message exchange. We used 200 nodes each with 26 transceivers using 400 mrad divergence angle. There were 8 GPS-enabled nodes and we ran the simulations for 10 iterations. We ran two separate simulation setups for this scenario. In the first setup, we placed the nodes on a 10x10x2 perfect grid and in the second setup, we placed all the nodes randomly. As depicted in Figure 4, we saw that placement of nodes on the terrain is a significant factor in extent of localization and message exchange overhead. First setup with deterministic placement reaches over 90% localization extent in 10 message exchanges. However, the setup with randomly placed nodes reaches 90% after 90 message exchanges and 80% after 33 message exchanges.

4.4 Summary

In this chapter, we proposed a novel approach to the problem of node localization in stationary ad-hoc networking context via multi-element free-space-optical antennas as published in [43]. We used readily available directionality information to perform a simple triangulation. Our approach has low processing needs and does not need a complex tuning phase, or extra hardware. We conclude that optical wireless is attractive both because of its high throughput and because of its easy to exploit directionality benefits that help solving the localization problem.

Chapter 5

Prototype Hardware Setup, Proof-of-Concept Experiments and LOS Performance Experiments

5.1 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:

Figure 5.1: Hardware setup: transceiver is connected to a laptop pc.

- PIC16F877A
- PIC24FJ128GA106
- 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 could 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

Figure 5.2: Hardware setup: laptop pc is connected to the microcontroller.

Max232 CPE for converting RS232 levels to TTL levels. In this current setup, shown in Figure 5.2, 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 5.3, 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.

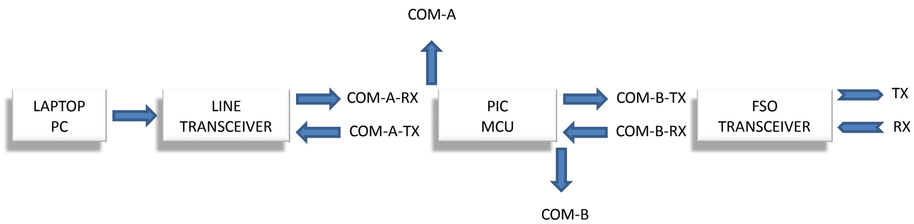


Figure 5.3: Hardware setup: FSO-Node with 1 transceiver and microcontroller.

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 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. Therefore, 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 a 16-bit microcontroller of Microchip family. This microcontroller has four 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. Therefore, 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 [3] 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.

5.2 Proof-of-Concept Experiments

5.2.1 LOS Alignment Algorithm

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 5.4 and 5.9).

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

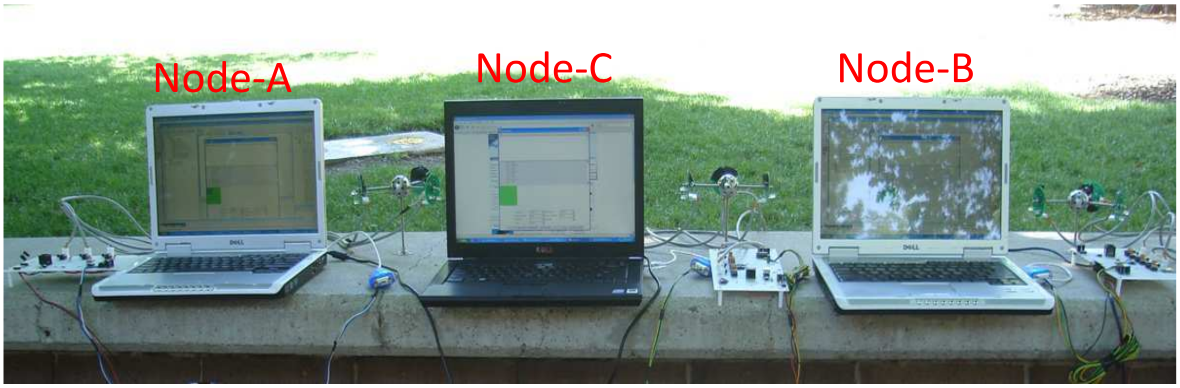


Figure 5.4: Experiment setup: 3 laptops (collinear placement), each with a 3 transceiver optical antenna.

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 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.

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 5.5) 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.

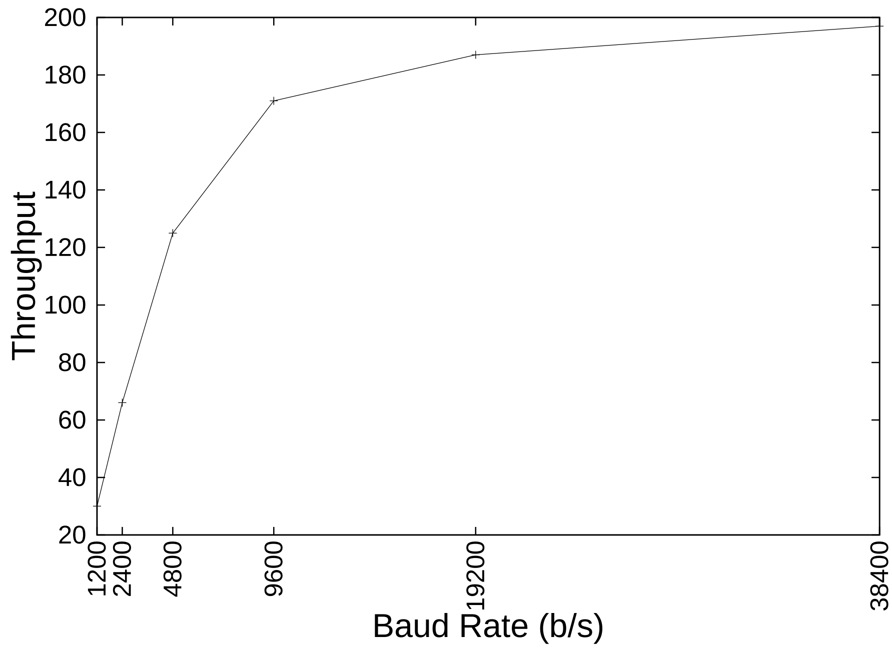


Figure 5.5: Throughput behavior as baud rate varies.

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 5.6) 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

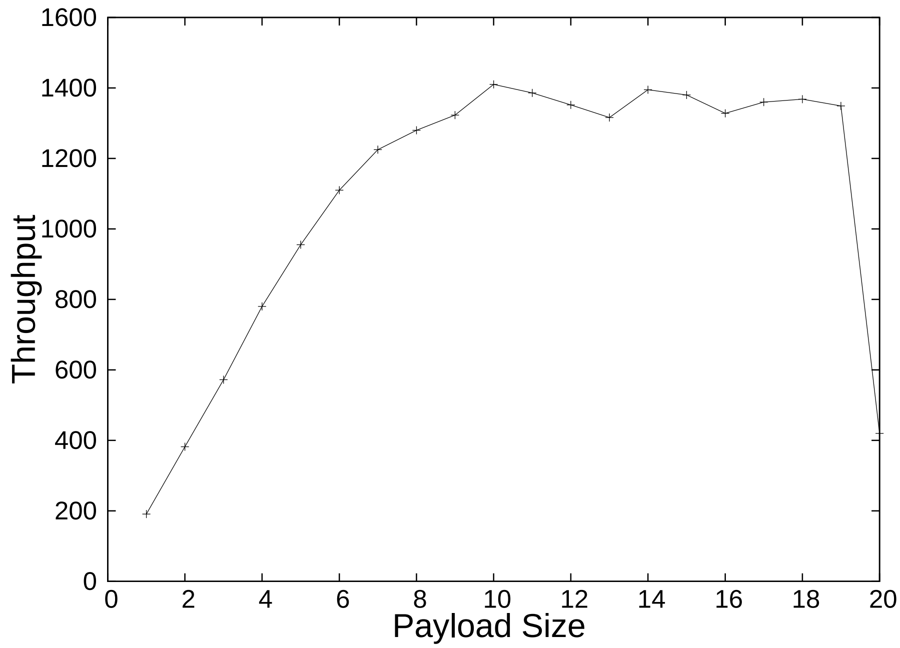


Figure 5.6: Throughput behavior as payload size varies.

maximum value.

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 5.7) 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

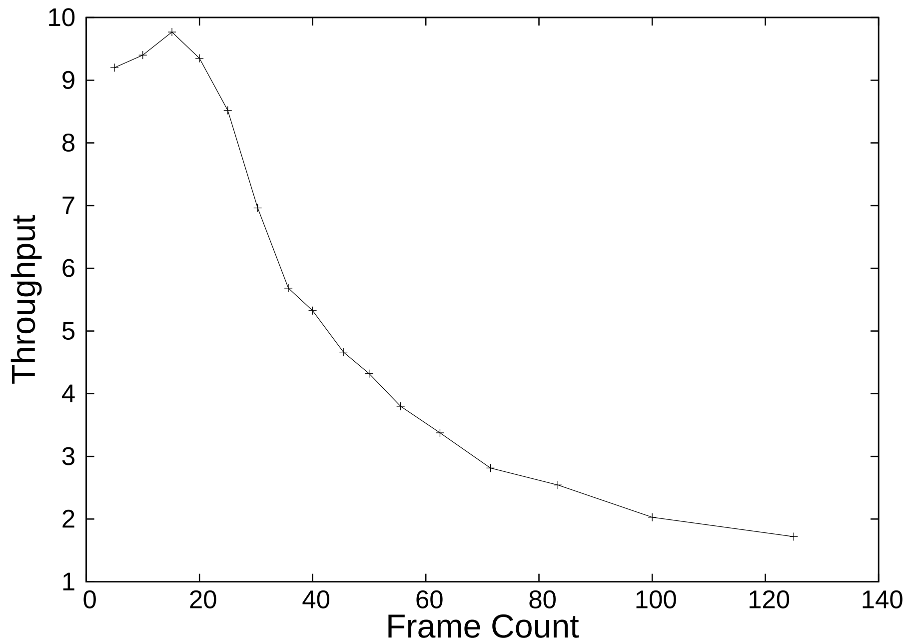


Figure 5.7: Frame count effect on channel usage.

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

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 5.8) 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.

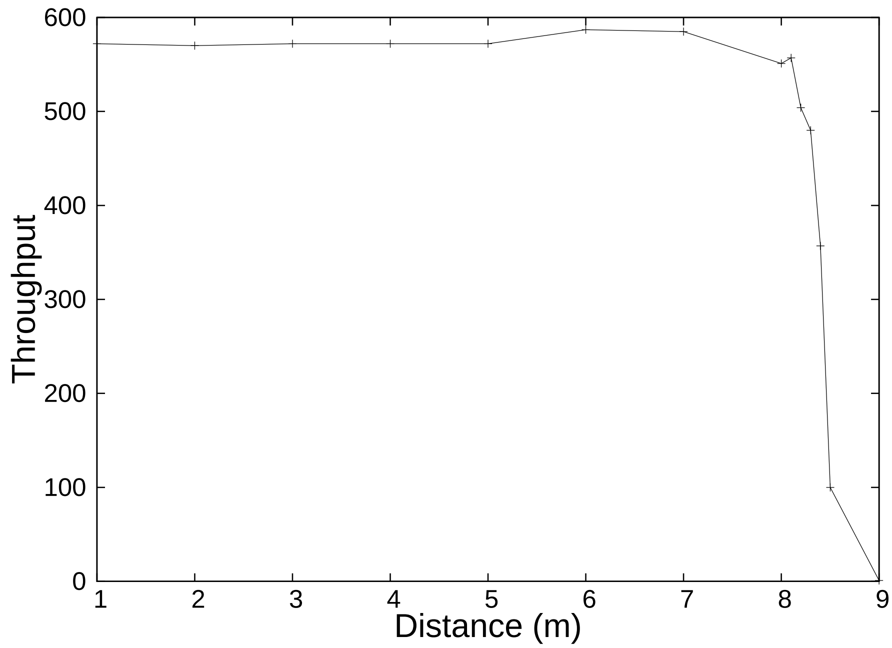


Figure 5.8: Distance effect on throughput.

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 5.9: 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.

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

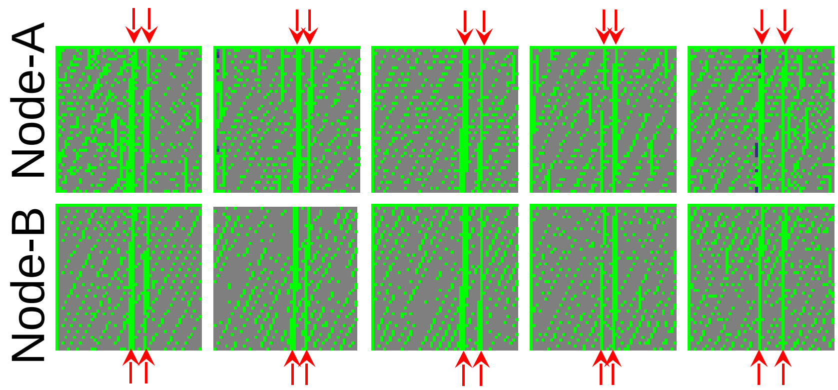


Figure 5.10: Experiment setup with 3 nodes and screen shots of a prototype experiment where transmitting node is mobile.

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 5.10. We saw that Node-C was able to successfully restore the data transmission every time after losing its alignments. Figure 5.10 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)

5.2.2 Basic Localization Scenario Experiments

The prototype exchanges localization packets among corresponding transceivers that are in line-of-sight of each other and it routinely probes for new alignments. Another can only send localization packets to one node node when the alignment is established between corresponding transceivers. The setup consists of 3 laptop computers labeled A, B and C, so that we can send localization packets among three nodes/laptops.

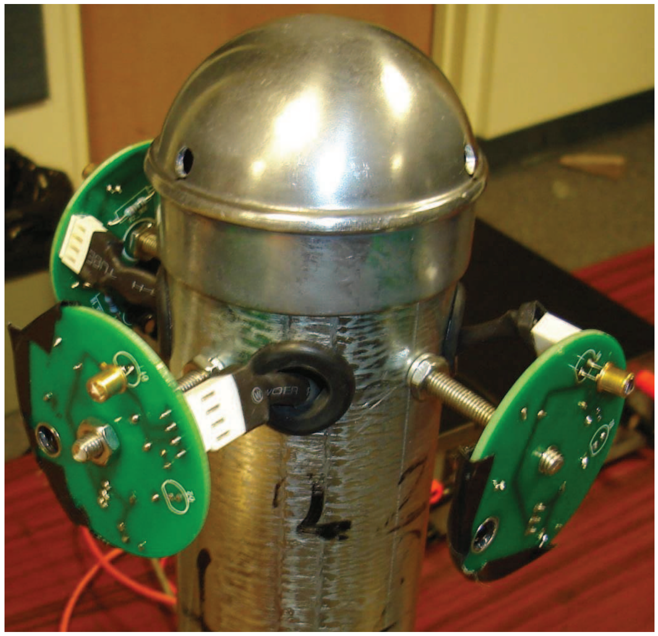


Figure 5.11: Optical antenna with transceivers and SFH 4881 is replaced on to transceivers.

We implemented software running on the laptop PCs, which we can configure, the node locations and normal (the relative angle that a transceiver is pointing to) of the transceivers that a node corresponds. When the alignment is established, localization packets are sent at this initial configuration setup. We have to pre-configure the normal when we turn a node since the relative angle that the transceiver is pointing to changes.

Our goal in experimental setup is to show that it is possible to achieve localization by using directionality of the free-space-optical communication in ad-hoc environments. In this setup, we use three nodes with three transceivers, and show that it is possible to achieve localization even with three transceivers per node. We envision packaging of tens of transceivers per node and achieving practical and highly accurate localization. Two of the three nodes in our setup stays at a fixed position when the third node is moving on an arc of a semi-circle. We have established two

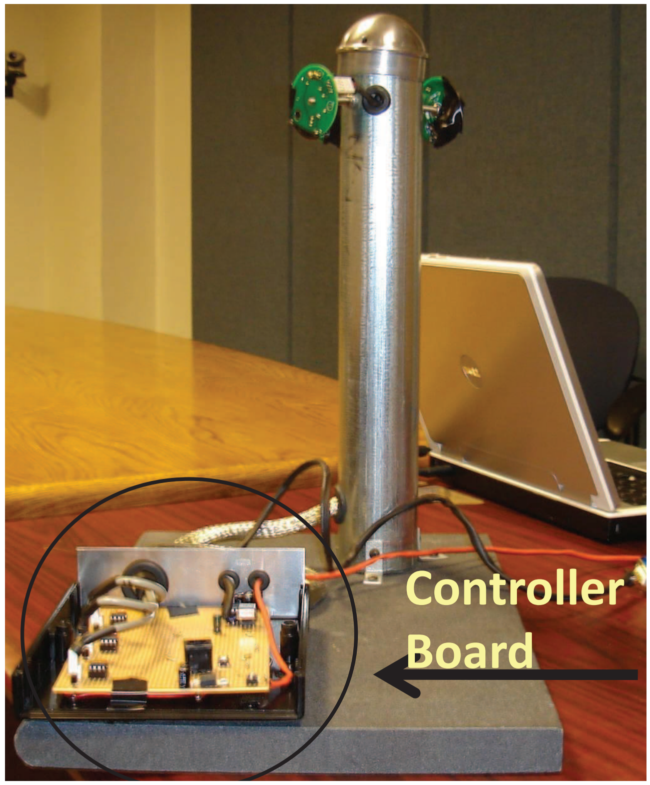


Figure 5.12: Picture of controller board.

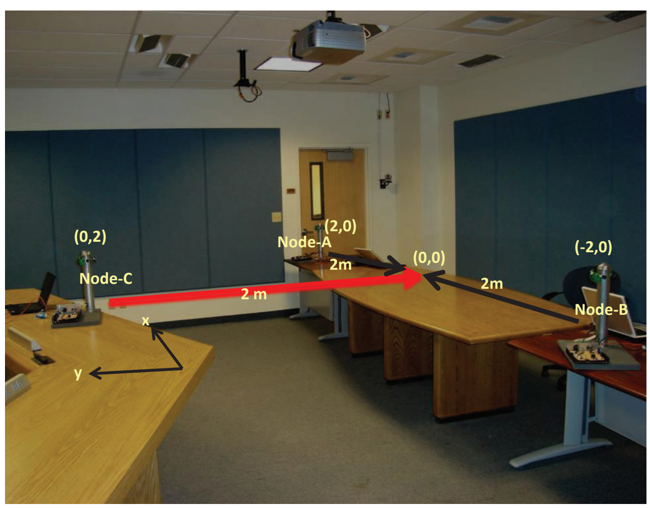


Figure 5.13: 2m experiment setup: Node-C is perpendicular to the diameter.

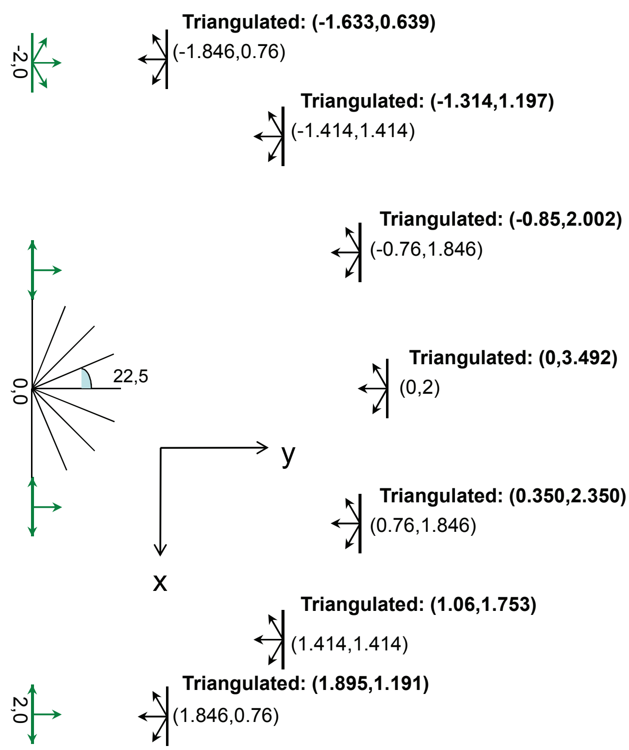


Figure 5.14: Experiment setup: The actual locations and triangulated locations for the 2m setup. Node-C is placed at 7 different locations.

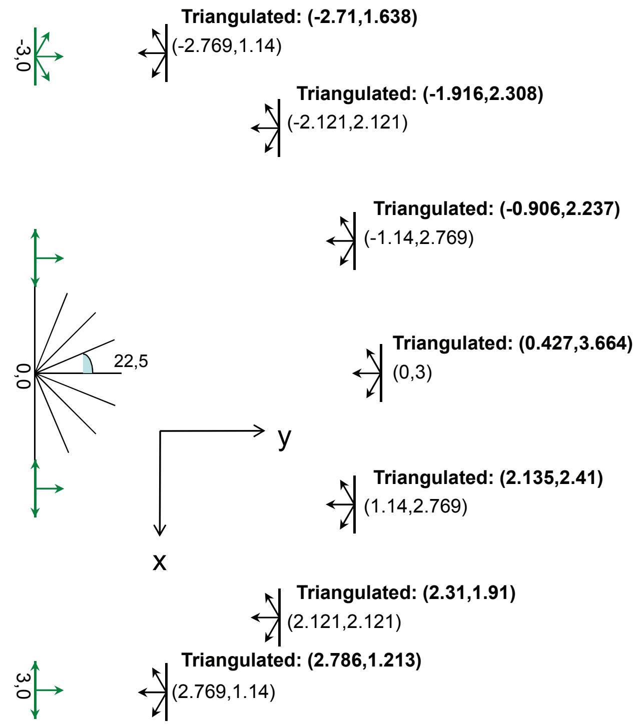


Figure 5.15: Experiment setup: The actual locations and triangulated locations for 3m setup. Node-C is placed at 7 different locations.

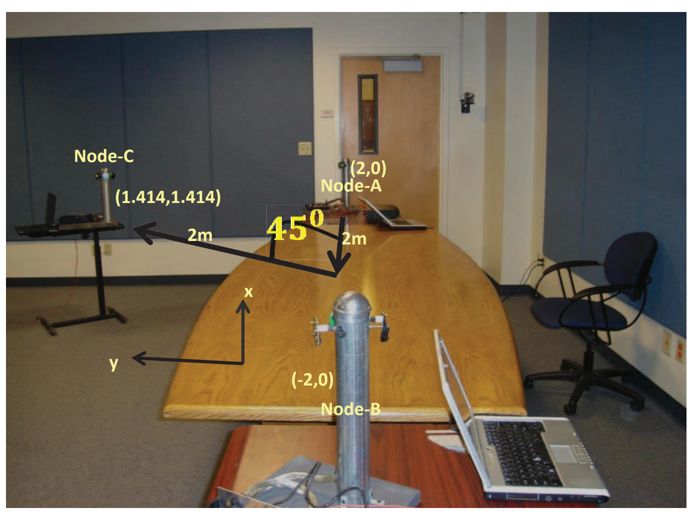


Figure 5.16: 2m experiment setup: Node-C is placed at 45 degree with x axis.

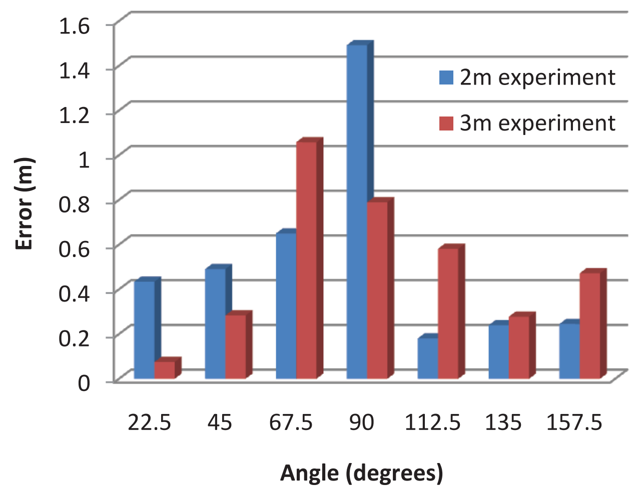


Figure 5.17: Error behavior between two points for the 2m and 3m experiments at corresponding angle values.

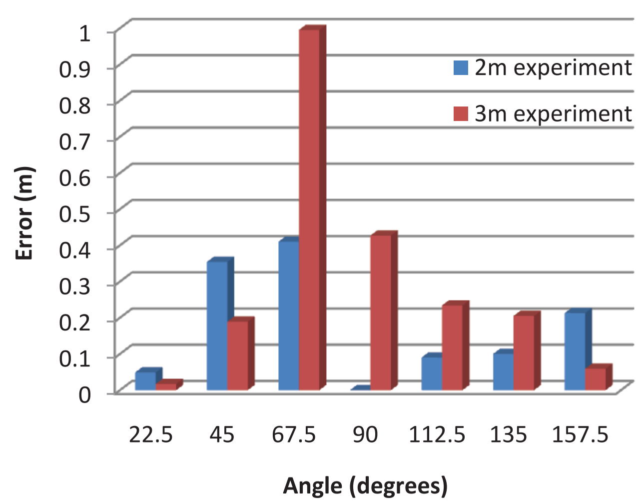


Figure 5.18: Error behavior at x axis for the 2m and 3m experiments at corresponding angle values.

experimental setups: 2m and 3m experiments. In the first setup, i.e., the *2m experiment*, we placed Node-A and Node-B 4 meters apart which is the diameter length of the semi-circle on which Node-C travels. The center of the diameter is the center of the coordinate system, i.e., the location (0,0). Considering this coordinate system, Node-A is placed at location (2,0) and Node-B is placed at location (-2,0), as shown in Figures 5.13 and 5.16. Node-C was moved among 7 different locations on the arc of this semi-circle. Starting at Node-B's location, each location on the arc has 22.5 degrees angle difference with respect to the coordinate (0,0). Figure 5.14 shows the placements of the nodes in the experiment setup. We used SFH 4881 in our experiments which has 15 degrees angle of half intensity measured at our lab experiments. Thus, there were blind spots in the arc of this semi-circle which we didn't receive localization packets. We turned around each node in order to establish the alignments so that localization packets were received by the three nodes for each of the 7 arc locations. We calculated normal of the aligned transceivers and calculated the location of Node-C by applying the Closest-Point-Of-Approach Of The 2 Rays approach described in Chapter 4. In our second experiment setup, i.e., the *3m experiment*, we increased the diameter of the arc to 6m. Similar to the first setup, we placed Node-A at location (3,0) and Node-B at location (-3,0). Node-C was moved among 7 different locations with a radius of 3 and 22.5 angle difference starting at point B, as shown in Figure 5.15. The number of blind spots that we have in this setup is increased compared to the previous setup. We were also able to receive localization packets in this setup at the 7 different locations although finding the critical points when turning over the transceivers to get localization packets were not as easy as in the previous setup. Based on the experiments, we calculated three different error values. The first error value is based on the error at x axis which is the absolute value of

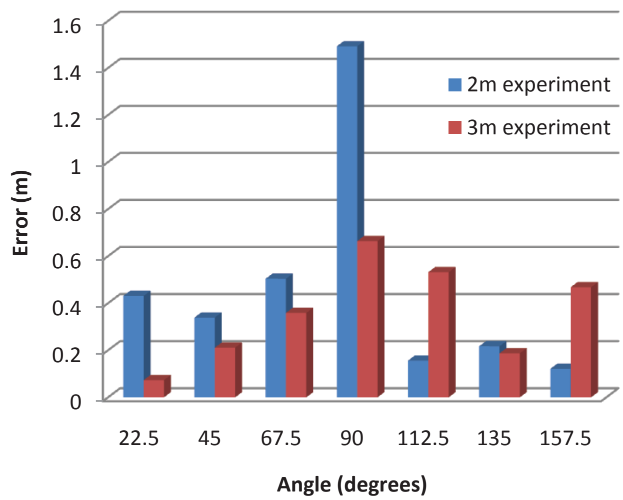


Figure 5.19: Error behavior at y axis for the 2m and 3m experiments at corresponding angle values.

the difference between the actual location of Node-C at x axis and the triangulated location at x axis (Equation 5.1). The second error value is based on the error at y axis. We again took the absolute value of the difference between the actual location at y axis and the triangulated location at y axis (Equation 5.2). Third error value is the distance between the actual (x,y) location of the node and the triangulated (x,y) location of the node (Equation 5.3). We can formalize our error values as follows:

$$Error_x = |X_{actual} - X_{Triangulated}| \tag{5.1}$$

$$Error_y = |Y_{actual} - Y_{Triangulated}| \tag{5.2}$$

$$Error_{xy} = \sqrt{(X_{actual} - X_{T.})^2 + (Y_{actual} - Y_{T.})^2} \tag{5.3}$$

Figures 5.17 and 5.19 show the error values at corresponding angle values for 2m and 3m experiment setups. As can be seen from the Figure 5.17, there is an increase at error rates when Node-C is placed on the y axis, meaning that the angle between the x axis and the node is 90 degrees, i.e., they are perpendicular. Error rates decrease when the node is moved to the left or right of this point. Figure 5.19 shows that the error during the 2m experiment was less than the error during the 3m experiment at some points, and vice versa. Larger diameter seems to favor locations closer to the 90 degrees location, i.e., when Node-C is closer to the y axis. For both diameter values, there is an increase at error values when we are close to the y axis. Since the error values of the 2m and 3m experiments are pretty close to each other, it is not possible to define a clear difference based on the diameter.

5.3 Experiments for LOS Performance Measurement Prototype over a Voice File Transfer

We experimented with our second prototype to measure the performance of a voice file transfer over a multi-transceiver FSO communication structure. The experiment setup consists of three laptop computers and three PIC32 Ethernet Starter Kits (e.g. controller boards). We connected two transceivers to laptop computer-A, one transceiver to laptop computer-B, and another transceiver to laptop computer-C, as shown in Figure 3.9. We conducted three experiments with our prototype. First experiment measures the performance of the transceivers and second experiment measures the performance of an image file transfer which is sent from Node-A to both Node-B and Node-C at the same time. Finally, we transfer different voice files to measure the performance of voice file transfer.

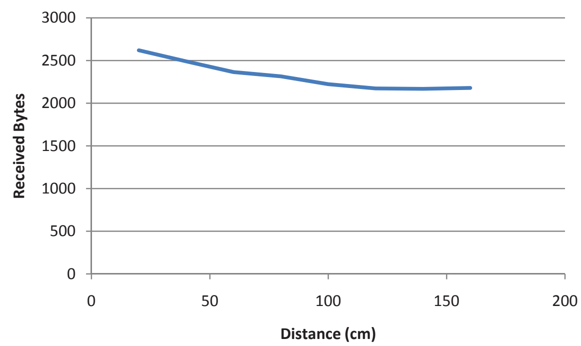


Figure 5.20: Transceiver performance graph: Showing the number of received bytes at varying distances

5.3.1 Transceiver Performance Test

In this experiment, we transferred a portable document file (PDF) of 3,637 bytes long from Node-A to Node-B. First, we transferred the file making a reverse connection between Starter Kit's UART transmit (TX) and receive (RX) pins by a cable connection. We transferred the whole file by success in this setup. Next, we connected the transceivers to Node-A and Node-B. The distance between Node-A's transceiver and Node-B's transceiver is set to 20 cm. Then, we increased the distance between transceivers and measured the performance of the transceivers for various distances by comparing the number of received bytes against the length of the original file. Figure 5.20 shows the number of received bytes depending on the distance between Node-A and Node-B. As we increase the distance between transceivers, the received byte count decreases. The operational range for the transceivers is approximately 2-3 meters.

The achieved performance by the transceivers is very low considering the performance achieved by cable connection. The main limitation is the half-duplex FSO link between Node-A and Node-B. The MCP2120 cannot transmit and receive at the

Figure 5.21: Original image and received image files for image file transfer in half duplex mode. The very left picture represents the original image file and following images are received images at Node-B and Node-C accordingly.

same time from UART port. Hence, we used two MCP2120s for each node to establish a fully functional bi-directional FSO link. The performance is significantly increased when we transferred the file with a bi-directional FSO link. The file is completely transferred to Node-B with a bi-directional FSO link setup.

5.3.2 Simultaneous File Transfer

We also analyzed performance of simultaneous file transfer from Node-A to both Node-B and Node-C. In this setup, laptop computer-A sends a file to both Node-B and Node-C and the performance of the file transfer is measured accordingly. We transferred an image file from Node-A to both Node-B and Node-C. The length of the image file is 7,572 bytes. When the link is in half duplex mode, the received image has been displayed in very low quality. Figure 5.21 shows the original image and the received image side by side for this half-duplex case. When the link is in full-duplex mode, the image has been displayed in a quality closer to its original although some frames are lost. Figure 5.22 shows the original image and received images for the full-duplex case.

Figure 5.22: Original image file and received image files for image file transfer in full duplex mode. The very left picture represents the original image file and following images are received images at Node-B and Node-C accordingly.

MOS	Rating	Perceived Quality
4-5	Excellent	Toll Quality
3-4	Good	Cell Phone Quality
<3	Fair	Unacceptable
<2	Bad	Unintelligible

Table 5.1: Mos Quality Table

5.3.3 Performance of Voice File Transfer

In this experiment we transferred 6 different voice files from one node to another, where Node-A transferred a voice file to Node-B. The communication link between the two nodes is set as a bi-directional FSO link. To measure the performance of voice file transfer, we used Mean Opinion Score (MOS) which stands as an industry standard for call quality [16]. The MOS is defined on a scale of 1 to 5, and Table 5.1 shows the scale of the MOS and consequent quality perception. MOS scale is designed for rating purposes to allow human subjects to grade their perception of quality during a call.

In our work, we have used automated methods to conduct quality analysis of voice experiment instead of evaluations made by human subjects. We measured the call quality via end-to-end tests by using standard implementation provided by International Telecommunication Union (ITU) [9]. Perceptual Evaluation of Sound Quality (PESQ) is the most adopted standard for automated measurement of quality,

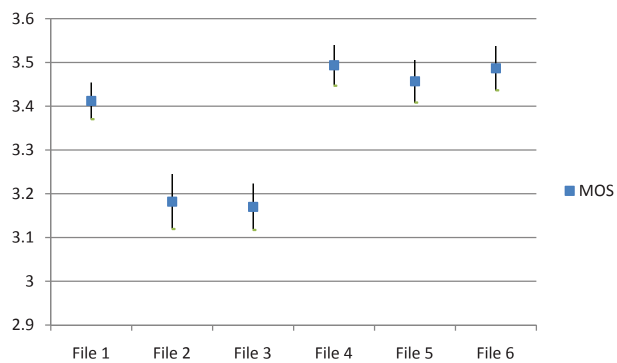


Figure 5.23: Voice file transfer performance graph. The MOS values are between 3 and 4 which stands as a good quality.

which is calculated by comparing the voice samples received over VoIP with the original voice samples. PESQ provides a mechanism to translate voice quality into consequent MOS scores that are gathered from human judges [9]. We have used sample files given by [9] which provide various background and sampling quality challenges. For each voice file transfer, we repeated the experiments for 30 times and calculated PESQ/MOS values for each voice file. We conducted the same experiment for 6 different voice files. Figure 5.23 shows the average performance in terms of MOS scores for 6 different voice files within 95th percentile confidence interval. The achieved performance reflects values between 3 and 3.8 which indicates a good quality based on MOS Quality Table 5.1.

In addition, we analyzed the voice transfer performance with increasing distance between transfer nodes. As depicted in Figure 5.24, our prototype sustains call quality performance within close proximity, i.e., 225 cm. Beyond this diameter, call quality drops to low levels, reflecting the overall nature of FSO communications with a thresholded performance. In our work, we have used only off-the-shelf, low-cost transceivers, which are limited in their transmission range. However, even with lim-

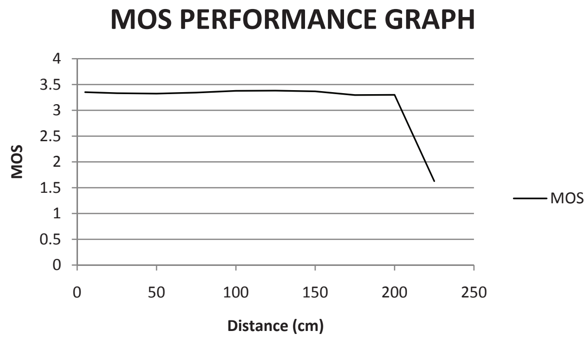


Figure 5.24: Voice file transfer performance graph based on varying distances

ited transmission range, by exploiting directionality, FSO communication provides high-performance local communication.

5.4 Summary

In this chapter, we presented our prototype experiments to show that it can successfully hand off multiple simultaneous data streams targeted to different neighbors. We presented set of mobility experiments that proves the feasibility of using multiple transceivers on FSO networks. We also provided set of voice file transfer experiments to show the performance of LOS protocol. Lastly, we provided basic localization experiments to conform simulations results of our localization approach.

Chapter 6

Transceiver Selection for Multi-Element Free-Space-Optical Communications

This section focuses on transceiver selection mechanism and our simulation efforts in NS-2 environment. We present simulation results and performance of our transceiver selection mechanism with various simulation parameters and their effects on end-to-end throughput performance over an FSO-MANET using multi-element spherical FSO nodes.

Free-space-optical (FSO) communication serves as a wireless technology complementary to RF for the future computer networks. The technology has many undiscovered opportunities beyond it is different use cases. One use case is using multiple FSO transceivers which propagates directionally where this directionality can be maintained by electronic steering. However, activating many transceivers for electronic steering on a spherical FSO node is not efficient.

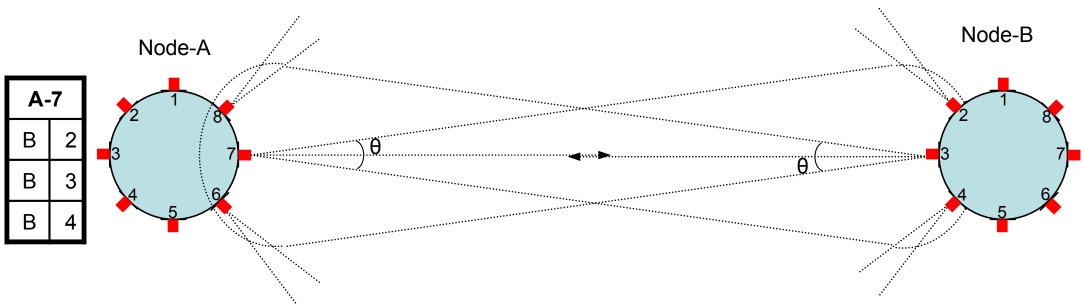


Figure 6.1: Multi-element antenna design in 2D view and sample alignment table kept in interface 7 of node A. [42]

Parameter Name	**Default Value**
Number of nodes	49
Number of flows	49x48
Visibility	6 km
Number of interfaces	8, 16, 24
Mobility	1 m/s
Simulation time	3000 s
Transmission range and separation between nodes	30 m
Area	210 m by 210 m
Node radius	20 cm
Divergence angle	0.5 rad
Photo detector diameter	5 cm
LED diameter	0.5 cm

Table 6.1: Table of default parameter values common to each simulation set in our experiments. [42]

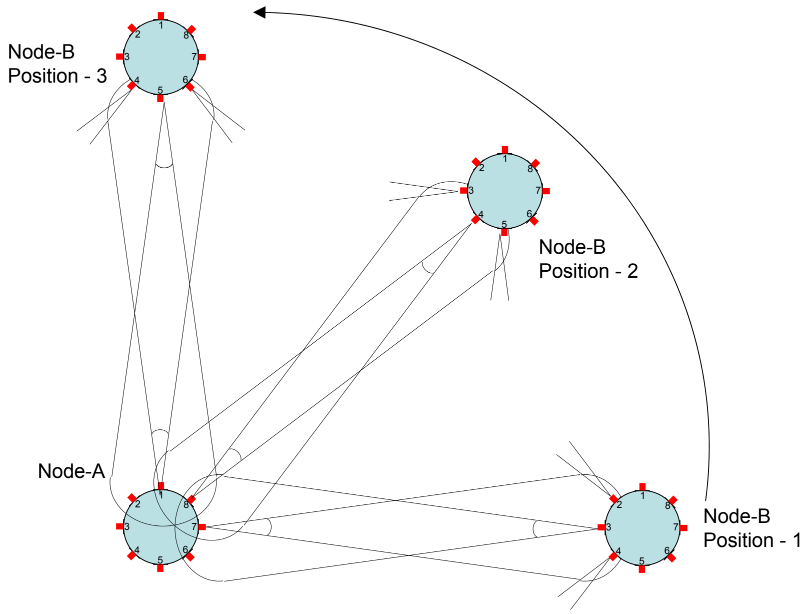


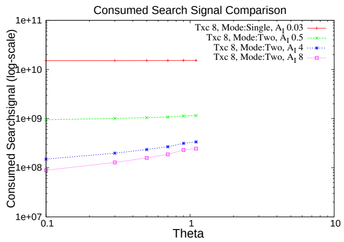
Figure 6.2: Sample alignment scenario for two mobile nodes. [42]

When many transceivers are deployed on a spherical FSO node, maintaining the power consumption in realistic regions is a major problem. Another problem is the hardware limitations of the current controllers. Further, providing a transmission medium for multiple transceivers requires many I/O interfaces, and implementing lots of I/O interfaces on a controller board is not cost effective. Such a system may not be scalable when packaging multiple transceivers on a spherical structure. The selection strategy becomes more challenging when this limitation is considered for an ad-hoc environment where many FSO nodes with multiple transceivers are communicating with each other. Therefore, the challenge is to select an *optimal subset* and to decide on an *optimal order/schedule* of how to incorporate the transceivers in the network for fast and efficient alignment.

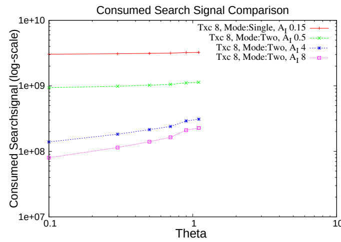
The selection strategy must also satisfy the maintenance of the LOS alignment under disruptions that are caused by the mobility of the communicating nodes since there is an uncertainty of the locations and movements of the mobile nodes in 3-D space. Therefore, we focus on transceiver selection algorithms and evaluate which mechanism is better by measuring the aggregate network throughput performance. In our simulation-based evaluations, we adhere to FSO propagation and transmission models in NS-2 proposed by Bilgi in [42]. We base our simulations on circular FSO nodes and deploy FSO transceivers on such nodes. Figures 6.1 and 6.2 show sample alignment scenarios for two mobile nodes and multi-element antenna design in 2D view with sample alignment table. We conclude our efforts with simulation results in the next section.

6.1 Selecting a Subset of Transceivers

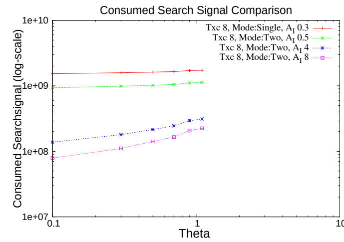
One of the possible solutions for selection mechanism is to select the closest transceivers on a circular FSO node and seek alignments of these closest transceivers when the alignment is lost. Our first approach was to send search signal periodically from all transceivers in a specific time period called alignment timer. We call this approach as *discovery interval alignment detection mechanism*. In discovery interval alignment detection mechanism, when the timer was fired for the interval time, all of the FSO nodes in the environment send search signal from their corresponding transceivers to seek possible alignments. If alignment is detected each node establishes its alignment table. Therefore, each transceiver acts as a physical interface and keeps the table of alignments. Instead of sending search signal from all physical transceivers deployed on a node, we keep track of alignments in each period and check if the alignment still exists in the next period. If alignment does not exist, we seek alignment by selecting the next and previous neighbor of the transceiver, where "neighborhood" refers to



(a) Discovery interval times: 0.03, 0.5, 4, and 8 seconds-Maintenance interval time: 0.03 seconds.



(b) Discovery interval times: 0.15, 0.5, 4, and 8 seconds-Maintenance interval time: 0.15 seconds.



(c) Discovery interval times: 0.3, 0.5, 4, and 8 seconds-Maintenance interval time: 0.3 seconds.

Figure 6.3: Consumed search signal comparison at single-mode and two mode alignment scheme with 8 transceivers at each node. Discovery and maintenance interval times are variable.

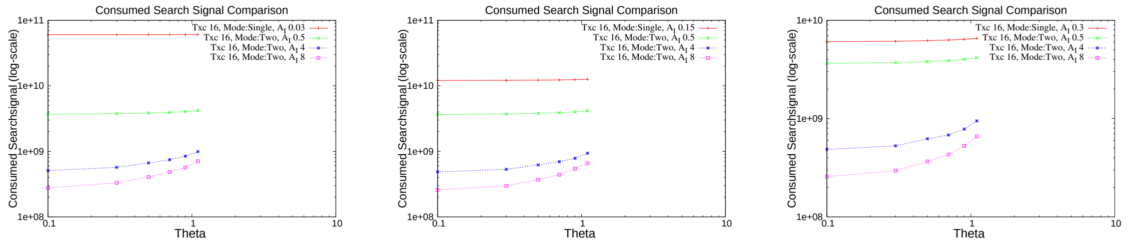
being the transceiver physically close to the one where alignment was lost. Therefore, the alignment is maintained continuously. We call this mechanism as *maintenance interval alignment detection mechanism*.

One problem can be detecting new possible alignments in the environment, since we only deal with the previous and next neighbor of the aligned transceivers. Thus, we also send search signal from all transceiver periodically but, not as many as in our previous alignment protocol. To evaluate the new alignment detection mechanisms we define two modes for the alignments. We define *single-mode* alignment detection where maintenance and discovery intervals are performed at the same frequency. Second, we define *two mode* alignment where these two intervals are performed at different time scales, with discovery interval being performed at sizably smaller frequencies.

To make alignment more efficient, we increase discovery alignment timer value and we keep the maintenance interval at a fixed value and smaller than discovery interval. Therefore, we decrease the number of search signals that are sent totally which reduce total power consumption and interference caused by search signals that are periodically sent over each transceiver at every node. The main goal of the maintenance interval is to keep the alignment alive by sending search signal from the closest neighbors of the transceivers when the current alignment is lost. Therefore, we define a specific time interval to maintain the alignments: maintenance interval. At each interval, nodes check if they keep alignment alive from the previous alignment condition. If the alignment is lost, the search signal is sent from previous or next neighbor of the transceiver which were aligned previously. If one of the neighbor nodes detects the alignment, it updates its alignment table for the alignment information. This procedure is done for every transceiver that has an alignment information in the alignment table. Second goal of the maintenance interval is to reduce the number of alignment search signals. Instead of sending alignment request from all transceivers, in the maintenance interval, search signals are sent from a number of specific transceivers (in this situation just the neighbor of the aligned transceivers) to keep alignment status alive. Therefore, number of alignment search signals is reduced significantly. This improvement provides less power consumption because most of the wireless systems consume power when they are in the search phase.

Since the maintenance phase only keeps alignments alive, there should be a mechanism to detect new nodes in the environment. Therefore, the primary purpose of the discovery interval is to detect new nodes in the environment and establish new alignments. The module seeks for new alignments at every discovery interval. Every transceiver in each node/module sends search signal and searches for the transceivers that are in line-of-sight of each other. If alignment exists, the node updates its alignment table.

In single-mode alignment operation, the maintenance and discovery procedures



(a) Discovery interval times: 0.03, 0.5, 4, and 8 seconds- Maintenance interval time: 0.03 seconds.

(b) Discovery interval times: 0.15, 0.5, 4, and 8 seconds- Maintenance interval time: 0.15 seconds.

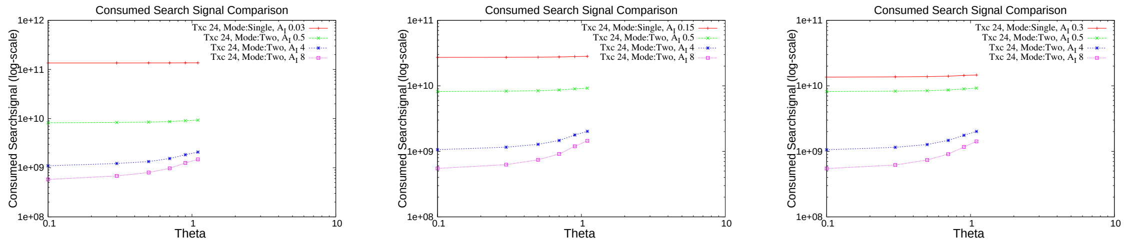
(c) Discovery interval times: 0.3, 0.5, 4, and 8 seconds- Maintenance interval time: 0.3 seconds.

Figure 6.4: Consumed search signal comparison at single-mode and two-mode alignment scheme with 16 transceivers at each node. Discovery and maintenance interval times are variable.

are performed at the same time scale, where we send search signal from all transceivers on an FSO node. Single-mode operation can provide better alignment detection since all the transceivers are active at the interval time. However, the major disadvantage of this mode is being inefficient to power consumption and interference because of the search signals that is being dissipated. In two-mode alignment operation, maintenance and discovery procedures are performed at different time scales. The main goal of this operation is to reduce the number of active transceivers and search signals in the search phase.

6.2 Simulation Results

In single-mode alignment detection scheme, the discovery and maintenance interval times are both set to 0.03, 0.15, and 0.3 seconds. In the two-mode alignment scheme we increased discovery interval times to 0.5, 4 and, 8 seconds and keep the maintenance interval values at 0.03, 0.15, and 0.3 seconds. We conduct the simulations for different number of transceivers respectively 8, 16, and 24. Simulations include 49



(a) Discovery interval times: 0.03, 0.5, 4, and 8 seconds-Maintenance interval time: 0.03 seconds.

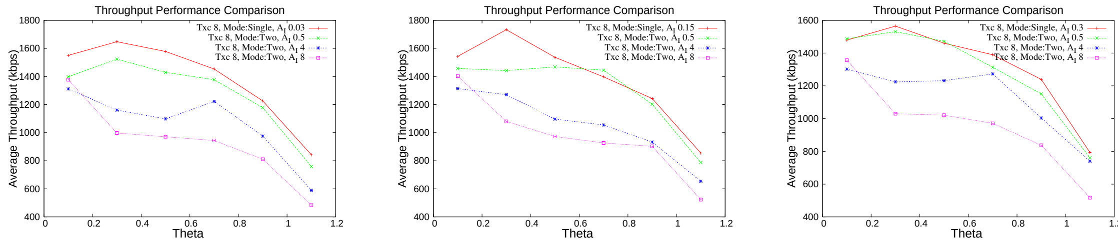
(b) Discovery interval times: 0.15, 0.5, 4, and 8 seconds-Maintenance interval time: 0.15 seconds.

(c) Discovery interval times: 0.3, 0.5, 4, and 8 seconds-Maintenance interval time: 0.3 seconds.

Figure 6.5: Consumed search signal comparison at single-mode and two-mode alignment scheme with 24 transceivers at each node. Discovery and maintenance interval times are variable.

nodes. Nodes are positioned in a 7x7-grid view at start time and they are mobile during the simulation. Every node opens FTP file transfer sessions using TCP to every other node in the network. Therefore, in the simulations there are 49x48 flows in total. All nodes are mobile moving at 1 meter per second with random waypoint mobility model. We used an area of 210x210 meters and the visibility of the medium was 6 kilometers. We ran the simulations for 3000 seconds and repeated in simulations for 10 iterations with different seed values. We compare FSO performance between single-mode and two-mode alignment schemes under the same conditions. We aim to answer the following research questions: How effective the two-mode alignment detection mechanism is compared to the single-mode alignment in terms of power consumption and end-to-end throughput?

Table 6.1 shows the *default* parameters we feed to our simulation experiments. The FSO node structures are circular in shape. Transceivers are placed on the nodal shape with a deterministic separation, i.e., the distance among any two-neighbor transceivers is the same. The node structure has a radius of 20 cm. The LEDs have

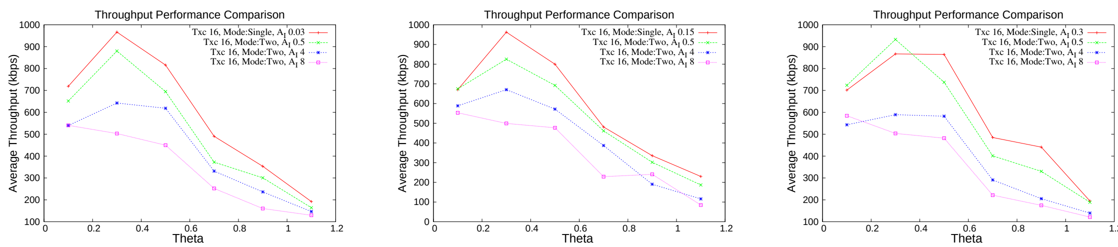


(a) Discovery interval times: 0.03, 0.5, 4, and 8 seconds-Maintenance interval time: 0.03 seconds.

(b) Discovery interval times: 0.15, 0.5, 4, and 8 seconds-Maintenance interval time: 0.15 seconds.

(c) Discovery interval times: 0.3, 0.5, 4, and 8 seconds-Maintenance interval time: 0.3 seconds.

Figure 6.6: Throughput performance comparison at single-mode and two-mode alignment scheme with 8 transceivers at each node. Discovery and maintenance interval times are variable.



(a) Discovery interval times: 0.03, 0.5, 4, and 8 seconds-Maintenance interval time: 0.03 seconds.

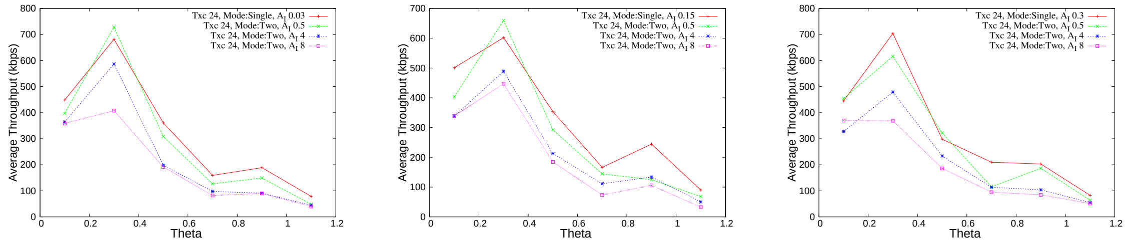
(b) Discovery interval times: 0.15, 0.5, 4, and 8 seconds-Maintenance interval time: 0.15 seconds.

(c) Discovery interval times: 0.3, 0.5, 4, and 8 seconds-Maintenance interval time: 0.3 seconds.

Figure 6.7: Throughput performance comparison at single-mode and two-mode alignment scheme with 16 transceivers at each node. Discovery and maintenance interval times are variable.

0.5 cm and PDs have 5 cm radius.

Figures 6.3, 6.4, and 6.5 show the number of search signals sent at varying maintenance and discovery intervals for single-mode and two-mode alignment schemes and different interface counts. Since most of the power is consumed at the search/discovery phase, we define the number of search signals as power the consumption metric. As shown in Figures 6.3, 6.4, and 6.5, the two-mode alignment scheme consumes an order of magnitude less power compared to the single-mode alignment scheme. The



(a) Discovery interval times: 0.03, 0.5, 4, and 8 seconds-Maintenance interval time: 0.03 seconds.

(b) Discovery interval times: 0.15, 0.5, 4, and 8 seconds-Maintenance interval time: 0.15 seconds.

(c) Discovery interval times: 0.3, 0.5, 4, and 8 seconds-Maintenance interval time: 0.3 seconds.

Figure 6.8: Throughput performance comparison at single-mode and two-mode alignment scheme with 24 transceivers at each node. Discovery and maintenance interval times are variable.

difference between the two schemes does not seem to be affected noticeably when the divergence angle, θ, varies. Figures 6.6, 6.7, and 6.8 show the throughput performance at varying maintenance and discovery intervals. The number of transceivers changes from 8 up to 24 and we increase the divergence angle from 0.1 radian to 1.1 radians. One must note that, as we increase the divergence angle of transceivers the coverage area of a node starts to resemble to that of RF. If the divergence angle is further increased, adjacent beams on a node start to overlap and cause crosstalk and interference. This is why we see a decrease in the overall network throughput in Figures 6.6, 6.7, and 6.8.

When the discovery interval time value is increased, we observe a throughput decrease. Our conclusion is that especially the decrease in throughput is not dramatically affected with larger timer intervals. This is an important finding to reduce the re-alignment overhead. However, compared to number of consumed search signals at single-mode alignment, one must note that, there is a tradeoff between the power consumption (i.e., the number of search signals sent) and throughput. Throughput does not decrease dramatically, however we observe a significant decrease in the search signals sent. Therefore, the two-mode alignment scheme performs better compared to the single-mode scheme, and presents a good tradeoff between throughput and power consumption. The best throughput performances are observed when the number of transceivers is 8 and theta value is 0.3 radian. Increasing the number of transceivers in our scenario did not increase the throughput performance because of the severe crosstalk and interference. However to gain better results, different deployment scenarios and theta values should be considered as we only focus on 7x7 grid topology in an area of 210x210 meters.

6.3 Summary

In this chapter, we presented our contribution to the NS-2 network simulator, mainly on the transceiver selection mechanisms for multi-element free-space-optical structures. We assessed the efficiency of varying simulation parameters on the overall network throughput for different alignment detection and maintenance schemes. We conclude that the new transceiver selection schemes with multiple modes of operation perform better than our previous alignment scheme. Further, different selection mechanism are also possible for different deployments and environmental conditions.

Chapter 7

Conclusions and Future Work

Free-space-optical communication with multiple transceivers has the potential for use as a next generation wireless technology. We demonstrated a prototype of such multi-transceiver spherical FSO nodes, which can successfully hand-off multiple data flows between FSO transceivers. We built the transceivers using off-the-shelf components to present the concept of spherical FSO nodes [147–150]. The line-of-sight alignment protocol is implemented to automatically hand off logical data flows among the physical FSO transceivers. We used different microcontrollers to implement the proof of concept prototype of such spherical FSO structures. Our FSO nodes consist of infrared LED and photo-detector pairs and we conducted several experiments using three laptops each with a circular FSO node utilizing three transceivers. 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 [45, 108].

We demonstrated another prototype, which uses LOS protocol and transfers voice files simultaneously with minimal disruptions and overheads [151]. The quality of the received voice proved to be comparable with commercial mobile phone service set by industry standards. As a promising performance is achieved by our simplistic FSO prototype, which highlights the promising capabilities of our approach that exploits directionality for FSO communication.

FSO technology is affected by building sway, which causes alignment disruptions. 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 by switching to 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 inner-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 electronic steering mechanism makes FSO technology applicable to mobile communications.

An advantage of FSO for multiple agent communication is directional nature of beams which can be used for localization. We demonstrated a prototype and conducted experiments to show that FSO can be used for localization and require less GPS enabled nodes for localization compared to other techniques [43]. We used directionality information to perform a simple triangulation with only two localized FSO nodes. We conclude that optical wireless is attractive to solve the ad-hoc localization problem.

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 consume less power while omni-directional antennas need more power to send the signal in all directions. Lastly, we introduced a different alignment detection scheme which is efficient than our previous alignment algorithm. Such algorithms are needed for dense packaging of many FSO transceivers on a single module to make FSO systems applicable to real world scenarios. We showed the performance of different alignment detection schemes in NS-2 simulations.

7.1 Future Work

Our prototype provides a basis for evaluation of performance characteristics of multi-element free-space-optical communications. We have conducted an extensive set of experiments to show that multi-element FSO communication is possible. We present multi-element FSO communication as a technology complementary to RF. Although RF is commonly used as a wireless technology, researchers should explore the multi-element FSO communication to solve the problems that exist in legacy wireless communication. Compared to FSO device sizes, RF components still have form factor issues that limit their dense packaging; and hence, result in limited spatial reuse. Therefore, we expect more research in multi-element FSO communication to draw attention for more use cases.

The current state of our prototype implementation is only able to provide slow transmission speeds since the focus of our work has not been designing high speed FSO structures but rather on the proof-of-concept for multi-element mobile FSO communications. We plan to design high speed transceivers to deliver significantly larger throughput using an increased number of transceivers. Hence, the increased number of transceivers will provide a higher throughput and better localization accuracy as well when the LEDs are calibrated for localization. We need smarter transceiver selection algorithms when the multi-transceiver designs reach multiple transceivers on each node.

Finally, we used simple triangulation with only two localized FSO nodes. However, more research is needed in further understanding how such multi-element FSO modules can be used to localize a large-scale network involving multiple obstacles and a heterogeneous set of angle-of-arrival detection capabilities among the nodes.

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