University of Nevada, Reno

Capacity Scaling in Free-Space-Optical Mobile Ad-Hoc Networks

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by

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To my loving mother and father.

Biricik annem ve babama.

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Abstract

Wireless networking has conventionally been realized via radio frequency (RF) based communication technologies. Main issue with RF networks is that end-to-end per-node throughput approaches zero as new nodes are added to the network. To overcome this throughput problem, we propose a multi-element optical antenna design that successfully exploits spatial reuse of the shared medium. In this design, each free-space-optical (FSO) transceiver (transmitter, receiver pair) element on a node is capable of maintaining a highly directional full-duplex transmission simultaneously with the other neighboring transceivers. We simulated networks of such nodes and found that FSO-based directional communication provides multiple times better channel usage. However, FSO nodes suffer from mobility for instance, since slight movement of communicating nodes can cause them to be *misaligned*, resulting in *intermittent connectivity*. In this thesis we present our findings related to free-space-optical mobile ad hoc networks (FSO-MANETs), effect of individual system parameters on transport level capacity scaling and compare FSO with RF networks within the context of MANETs.

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Chapter 1

Introduction

The capacity gap between RF (Radio Frequency) wireless and optical fiber (wired) network speeds remains huge because of the limited availability of the RF spectrum [16]. Though efforts for an all-optical Internet [4, 10, 15, 21, 46, 51] will likely provide cost-effective solutions to the last-mile problem within the *wireline* context, high-speed Internet availability for mobile ad-hoc networks is still mainly driven by the RF spectrum saturation and spectral efficiency gains through innovative multi-hop techniques such as hierarchical cooperation with multiple-input multiple-output (MIMO) physical layer [9]. FSO (Free-Space-Optical wireless) provides angular diversity and spatial reuse, which makes FSO even more attractive when combined with its optical transmission speed. However, FSO requires clear line-of-sight; contrary to RF, beam propagation is not omni-directional, which creates a challenge for mobile FSO deployments.

Mobile communication using FSO is considered for indoor environments, within a single room, using diffuse optics technology [18, 20, 38]. Due to limited power of a single source that is being diffused to spread in all directions, these techniques are suitable for small distances (typically tens of meters), but are not suitable for longer distances. FSO has received attention for high-altitudes as well, e.g. space communications [64] and building-top metro-area communications [5, 6]. Various techniques have been developed for such fixed deployments of FSO to tolerate small vibrations [56,57], swaying of the buildings, using mechanical auto-tracking [24,39,44] or beam steering [66]; but none of these techniques target mobility.

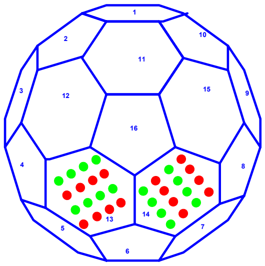


Figure 1.1: Multi-element antenna design tessellated with transceivers.

Similarly, for optical interconnects, auto-alignment or wavelength diversity techniques improve the misalignment tolerances in 2-dimensional arrays [19, 22, 28, 29, 42]. These techniques involve cumbersome heavy mechanical tracking instruments. Moreover, they are designed to improve the tolerance to movement and vibration but not to handle mobility. Thus, mobile FSO communication has not been realized, particularly for ad hoc networking and communication environments.

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

To counteract these numerous advantages, FSO requires clear line-of-sight (LOS), and LOS alignment between the transmitter and receiver for communication. FSO communication also suffers from beam spread with distance (tradeoff between per-channel bit-rate and power) and unreliability during bad weather (especially fog).

FSO mobile ad-hoc networks (FSO-MANETs) can be possible by means of "optical antennas", i.e., FSO spherical structures like the one shown in Figure 1.1. Such FSO spherical structures achieve *angular diversity* via spherical surface, *spatial reuse* via directionality of FSO signals, and are *multi-element* since they are covered with multiple transceivers (e.g., LED and photo-detector pair). In this thesis we investigate scalability behavior of networks and effects of multi-element FSO structures to upper layers, i.e., IP layer and transport layer.

Our findings reveal that because of spatial reuse, end-to-end per node throughput of FSO nodes can be multiples of magnitude of RF, both in stationary and mobile scenarios; while RF experiences a linear scalability bottleneck even with hierarchical cooperative MIMO [9]. Additionally, packaging increased numbers of transceivers (i.e., transmitter and receiver pair) on a node yield even better throughput with a decreased marginal gain for each additional transceiver because of deepened effect of interference.

Furthermore, FSO does suffer from its line of sight requirement when experimented in a mobile context; on the other hand RF does a reasonably well job, achieving a relatively stable line of throughput against increased mobility, but still lower than FSO. We also investigate dense deployment of such nodes (e.g., downtown area) with and without adjusted power and compare the results with FSO.

We found that throughput of FSO networks drop seriously while RF perform increasingly better where deployment of such networks is done in a large area, e.g., 10 km by 10 km and larger. The drop in FSO's performance is mainly because of coverage issues. Directional antennas can not provide a perfect coverage in such scenarios like RF does.

Also, we found out that the mobility of an FSO node causes its transceivers to loose their alignment with other transceivers in the network and re-gain it, in a short amount of time. We call this event of frequent alignment and misalignment "*intermittent connectivity pattern of free-space-optical structures*". We inspected implications of intermittent connectivity pattern on higher layers, especially on TCP (Transmit Control Protocol) and concluded that TCP gets severely affected.

Finally, RF and FSO are in fact complementary to each other. In a hybrid environment where nodes accommodate both RF and FSO capabilities and a suitable network stack that can take advantage of both technologies, RF can overcome FSO's coverage issues while FSO can meet the high-bandwidth requirements of the network.

This thesis is organized as follows: Chapter 2 provides a summary of relevant major research efforts in the literature, their common use cases and problems and solutions in those fields. Chapter 3 gives the details of FSO technology, propagation model of light in free-space and our NS-2 contributions, including various implementations of alignment-determining algorithms. Chapter 4 summarizes our research by discussing results of experiments that we conducted to reveal FSO's throughput potential in specific scenarios. We also detail our discussion on impact of multi-element communication mechanisms on higher layers. In Chapter 5, we lay out unresolved problems that can potentially increase the system throughput.

Chapter 2

Literature Survey

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

- high-speed FSO communications,
- mobile FSO communications,
- effects of FSO-like communications on higher layers of the networking stack.

NSF Mobile Planning Group [52] expects significant qualitative changes to the Internet that will be driven by the rapid proliferation of mobile and wireless devices. They advocate that modifications or a complete redesign of the Internet will be needed to support applications and architectures that are fundamentally different in nature like mobile and wireless device users and sensor-based applications. Those applications will need new emerging wireless network technologies such as mobile terminals, ad-hoc routers and embedded sensors to better enable end-to-end service abstractions and provide a more programmable environment for application development. They expect a diverse set of use case scenarios (Figure 2.1) that involve WiFi-hotspots, Infostations, mobile peer-to-peer, ad-hoc mesh networks for broadband access, vehicular networks, sensor networks and pervasive systems to drive the demand for new protocols' design and implementation that tightly integrates the mobile and stationary parts of the world.

They argue that a "clean-slate" architecture (i.e., disruptive design) will be needed to meet the requirements of mentioned use cases, in which the mobile and wireless devices reach billions in numbers (around 2 billion as of 2005) after evaluating other viable solutions: IP-overlays and extensions to IP. It also argues that there will be dramatical need for change in experimental research of networking, not just in wireless/mobile context but also in the context of large-scale end-to-end system evaluation. Such testbeds should facilitate programmable protocols running on wireless and mobile nodes that are also connected to programmable Internet backbone will provide a viable judgement of different approaches.

The group also introduces enhancements or replacement technologies for;

- Addressing and identity resolution for mobile nodes that change IP subnets without any application level challenges,
- Delay tolerant disconnected operations that enable new network services that caches commonly used data,
- Exploiting location awareness by using it as a routing mechanism and harnessing location-aware applications. Also gives suggestions on the representation of the location data, as latitude-longitude based (i.e., Universe Transverse Mercator) representation.

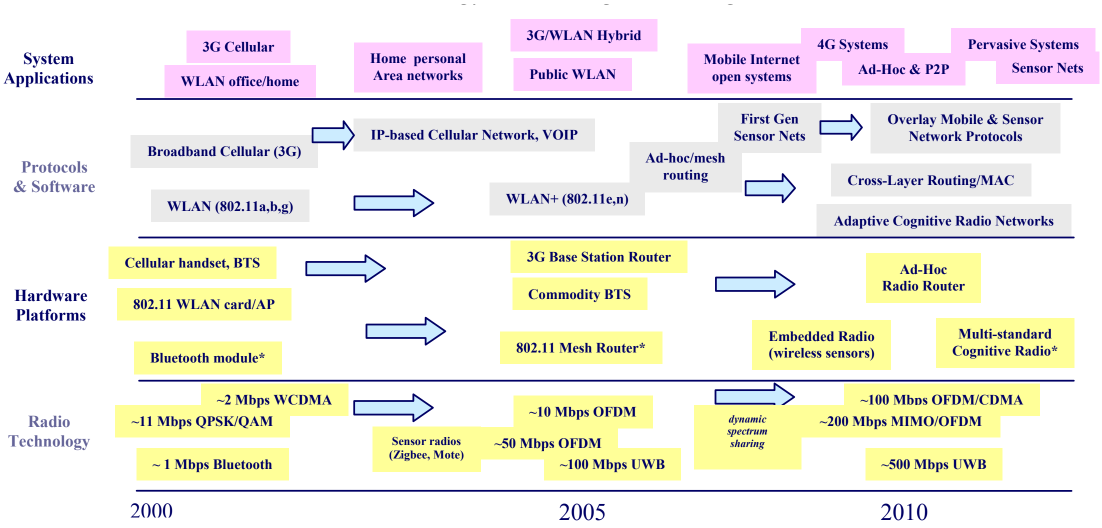


Figure 2.1: The expected roadmap of wireless technologies in 10 years. [52]

- Security and privacy. Primarily, radio jamming, denial-of-service attacks and authentication of location data.

- Deployment of self-healing and self-configuring network architectures since the traditional commercial management boundaries will be more blurred. Also foresees the new management instruments such as wireless channel characteristics and MAC and routing level information. Decentralized management for remote monitoring will be applied for configuration and control of distributed and heterogeneous wireless networks.

- Cross-layer protocol support that exposes valuable information among multiple layers. Moreover, reconsideration of protocol stack design from scratch.

- Cognitive radio networks that enable wireless devices to flexibly create many different kinds of communication links depending on required performance and spectrum/interference constraints.

The group strongly argues that the building blocks that will be deployed in future Internet should be experimented widely in an “Experimental Infrastructure (for Wireless Network Research)”. The wireless/sensor testbed should be integrated with a flexible wide-area network that can be used to study new architectures and protocols in an end-to-end fashion. For this experimental infrastructure, they give examples of open API radios and cognitive radios and virtualization of wireless MAC for innovative usage in selecting a medium access control (MAC) protocol, for the next session/packet, that suits best for the current medium based on previous observations. They conclude that the future Internet will undergo a fundamental transformation over the next 10-15 years, thus, a need to focus on central network architecture questions related to future mobile, wireless and sensor scenarios.

B. Metcalfe argues that all-optical networking infrastructure will take over the world as new types of multimedia applications that require more and more bandwith are seeing high demands from end users [14]. The article mentions Dr. David R. Hubert as one of the few people that influenced such a change by introducing 16-channel (16-lambda) dense wave division multiplexing hardware to the market as early as 1992. While the Dot-Com era saw start-up companies that came up with ideas like deploying fiber optical cables through the sewer canals [30], the fact that fiber-to-home projects failed is apparent.

Japan is leading the way in deploying optical links at large scale [4]. There is not much effort in such a massive deployment in US; just a handfull of proprietary deployments which include:

- FirstWorld started with an ambition to provide fiber connectivity in Orange County, CA, though not being able to cover the whole area. The company has changed its name to Vurado Holdings (2001) and was acquired by EarthLink in the same year.

- SpectraNet is close to total-coverage in Anaheim, CA.
- A Rye, Colorado community also has fiber deployed widely.
- Another fairly extensive fiber network providing high-speed Internet access as well as video broadcast is Intercable‘s system installed in Alexandria, VA
- GST Telecom (Seattle, WA) is also active in developing small, isolated high-speed fiber access, generally in planned communities
- Recently, the City of Palo Alto‘s public utilities department has started to offer fiber to the residence.

Since the time article was written, 1998, most of the companies are either closed or are acquired by other companies. However, this list serves our purposes; there has been efforts to provide wired optical connectivity in the history of communications, though failed to reach *every* home or business.

What the companies saw while deploying the technology over a decade is that the expected quick integration and demand from small businesses and homes was not realistic. People were less in search for the high bandwidth given the initial costs. Researchers conclude that 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 bandwith against copper-based technologies. Authors also give examples of so-called Premium Internet Service Providers including Concentric Networks, Frontier GlobaLAN, AboveNet, Digital Island, and NaviSite, as they no longer adhere to the routing schemes of the public

Internet. Instead, they have established private paths for data that avoid the congested public access points, the network access points, and Internet exchange points, in favor of data exchanges at restricted access switches owned by the fiber providers.

Demand for high-speed communication has always existed, even increasingly with more bandwidth-intensive multimedia applications of today. This demand from the end-user, is only being suppressed by internet service providers by charging with exponentially increased rates and fees. 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*.

This section provided an idea on the efforts of laying fiber in the last decade and their relatively minimal 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. As we indicated, the bottleneck in an end-to-end communication system is at the last mile. To remedy this long-experienced problem of low bandwith, we advocate easily deployable (not buried), re-locatable optical systems that are comparable to fiber in terms of bandwidth. Such systems will be considered as house-hold or business commodity, let alone being not thought as a sunk cost.

2.1 High-speed FSO Communications

Legacy optical wireless, also known as free-space-optical (FSO) wireless, communication technologies use high-powered lasers and expensive components to reach long distances. Thus, the main focus of the research has been on offering only a single primary beam (and some backup beams); or use expensive multi-laser systems to offer

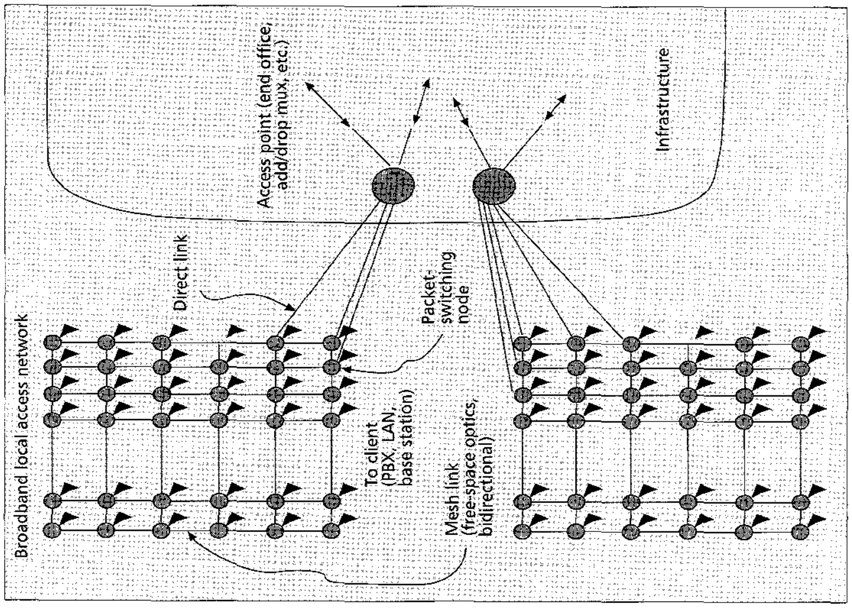


Figure 2.2: Basic architecture of the broadband access network [54]

redundancy and some limited spatial reuse of the optical spectrum [24,66]. The main target application of these FSO technologies has been to serve commercial point-to-point links (e.g., [5, 6]) in terrestrial last mile applications and in infrared indoor LANs [20,38,54,55,63,66] and interconnects [24,27,44]. Though cheaper devices (e.g. LEDs and VCSELs) have not been considered seriously for outdoor FSO in the past, recent work shows promising success in reaching longer distances by aggregation of multiple LEDs or VCSELs [1, 2].

2.1.1 Terrestrial Last Mile and Indoor Applications

Acampora *et al.* describes an approach to broadband wireless access using directional FSO links [54]. Key to this approach is its use of short, inexpensive, and extremely dependable focused free-space-optical links to interconnect densely deployed packet-switching nodes in a multihop mesh arrangement (Figure 2.2). Each node can then serve a client, which may consist of a building containing private branch exchanges (PBXs) and LANs (for fixed-point semice), a picocellular base station (for wireless semice), or both. 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. Acampora et al.'s work provides the most common use-case of FSO in today's applications; roof-top deployments through a high-powered laser components to reach long distances.

The authors of [47] examine possible performance improvements by changing receiver and transmitter hardware used in infrared wireless systems for short range indoor communication. Tweaked hardware includes: single-element receivers replaced by imaging receivers and diffuse transmitters replaced by multi-beam (quasi-diffuse) transmitters. Obtained power gain is from $13dB$ to $20dB$ while still meeting acceptable bit error rates (10^{-9} with 95% probability). The authors encourage usage of quasi-diffuse (i.e., multiple beams) transmitters since they leverage Space Division Multiple Access (SDMA).

O'Brien *et al.* provides an approach to fabricating optical wireless transceivers [18]. They use devices and components that are suitable for integration. The tracking transmitter and receiver components (diffuse transmitters and multi-cell photodetectors) have the potential for use in the wide range of network architectures. They fabricated and tested the multi-cell photo- detectors and diffuse transmitters, specifically seven transmitters and seven receivers operating at a wavelength of 980 nm and 1400 nm for eye-safety regulations. They designed transmitters and receivers to transmit 155 Mb/s data using Manchester Encoding. They compare optical access methods: a wide-angle high-power laser emitter scattering from the surfaces in

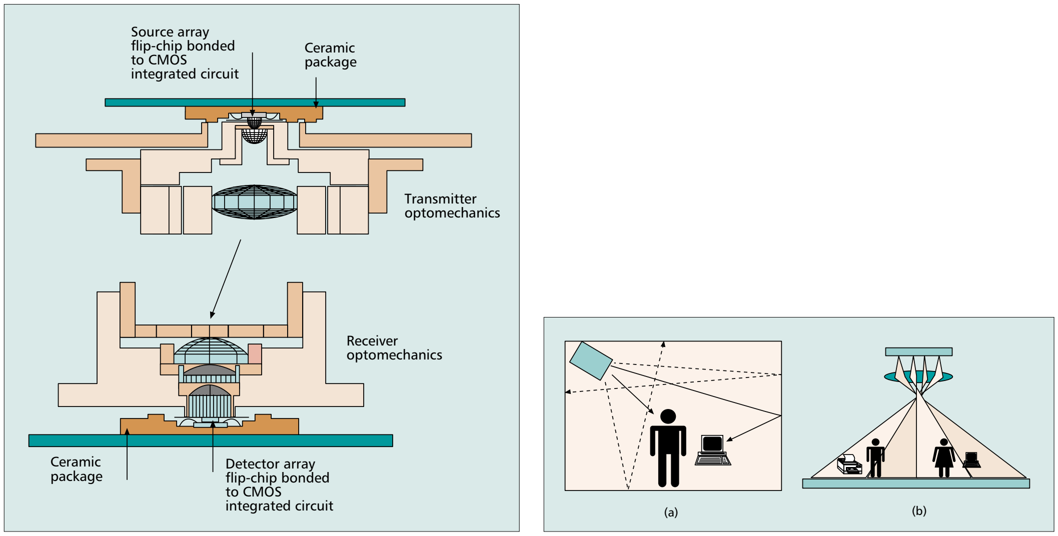


Figure 2.3: System of optomechanics [18]

the room to provide an optical ether or using directed line-of-sight paths between transmitter and receiver. In the first approach to transmitter design, although a wider coverage area is achieved, multiple paths between source and receiver cause dispersion of the channel, hence limiting its bandwith (Figure 2.3).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 last two papers proposed to use relatively directional beams (quasi-diffuse) to take advantage of directionality. Due to limited power of a single source that is being diffused to spread in all directions, these techniques are suitable for small distances (typically tens of meters); hence they can not be considered for longer distances.

2.1.2 Hybrid (FSO and RF) Applications

Yan *et al.* talk about RF based MANETs facing throughput demands and FSO being an complementary technology [48]. They introduce FSO capabilities to traditional RF-based MANETs. They advocate that pure-FSO MANET would be unrealistic because of the coverage and reachability issues caused by the extremely directional FSO beams. They conduct a search for commercially available hardware such as gimbals for steering the FSO beam. This is because the nature of the FSO technology that they target is fundamentally different than ours. The FSO beams that we advocate can potentially have a wide angle of transmission (divergence angle, θ), and dense packaging of such transceivers eliminate the need for complex mechanical steering methods. Our auto-alignment and tracking approach is fundamentally different in nature, which we will illustrate through specific circuitry later in Chapter 3. The authors conduct simulations of such hybrid networks in OPNET simulation environment. The number of nodes in the simulated network is far from being close to a realistic network; there are only 5 nodes, including a hub. Mobility pattern of nodes is predetermined and hard-coded. The average end-to-end delay that a packet experiences is 1.3 seconds, which is unexpectedly high. And, although the article starts with proposing simulation of hybrid nodes, it only simulates nodes that are FSO-capable; none of the 5 nodes has additional RF capabilities. This work stands out since it is the first attempt to simulate FSO with a reasonably realistic propagation model in free-space-optical communication literature.

The authors of [59] design a hybrid deployment of RF and FSO. FSO is mainly used as the high bandwidth backbone for the network. They focus on the “software”

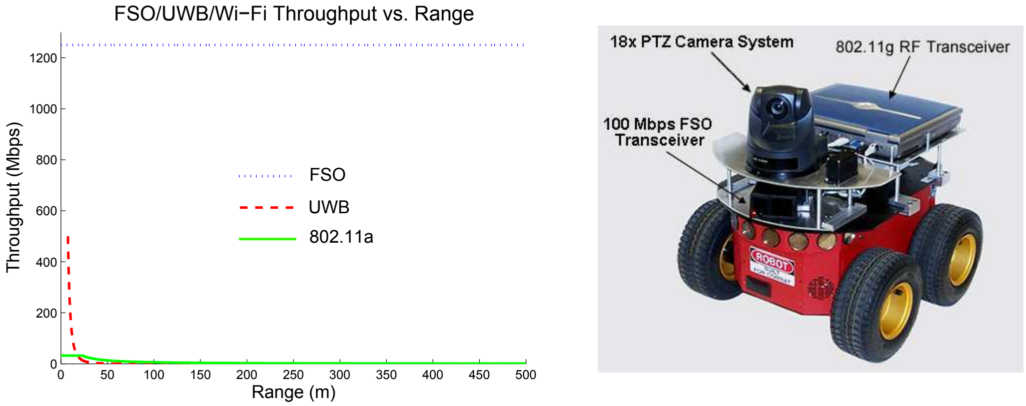


Figure 2.4: Throughput vs. range for FSO, UWB, and 802.11a technologies. Mobile robot with FSO/RF capabilities. [35]

that controls the network: topology and diversity control software module, combined with hardware that handles pointing, acquisition and tracking. This software should be aware of actual and potential connectivity of the network and exploit this information to provide best connectivity available. Hence, network is highly reconfigurable (i.e., self-configuring) leveraging an autonomous switching hardware between FSO and RF at the node level and pointing of FSO/RF aperture to re-establish an optimal network topology. Note that, since the described hardware (aperture) is shared by FSO and RF, the mentioned RF is *directional*, placing the reconfiguration software at a higher degree of importance. They evaluate the failure scenarios of FSO and/or RF links; failure of an FSO link can not be compensated only by RF because of the inherent bandwith gap. Scenarios like this impose another set of requirements on the control software in terms of efficient routing. Those responsibilities of control software are mapped to appropriate layer/sublayers in the TCP/IP stack.

According to Derenick *et al.*, RF links serve as a low-bandwidth backup to the primary optical communication link [35]. Both technologies are considered as accommodating significant weaknesses and they are complementary and have the potential to address each other's limitations (Figure 2.4). The article criticizes the much anticipated ultra wideband (UWB) technology - with theoretical throughput of 100s of Mbps - dropping to levels lower than 802.11a at modest ranges ($r \geq 15m$). Disaster relief applications are considered as the target application group. Also, they evaluate localization benefits of FSO. Mobile robots are selected as host to FSO and RF communication technologies. RF was seen performing unsatisfactory for surveillance video streaming task among robots, hence, FSO is used successfully for this bandwidth-intensive operation.

Additionally, the same authors designed a hierarchical link acquisition system for mobile robots to pair with each other in [36]. Alignment is aimed to work in three phases: coarse alignment using local sensors (robots are assumed to know each one's objective position) and positioning systems like GPS, refinement of line-of-sight using a vision based robot detection, and finally precise FSO alignment. The authors focus on the first two, leaving the third step to internal FSO tracking/pointing system. The paper also discusses Hierarchical State Routing (HSR) algorithm in which hybrid nodes are more outstanding candidates of being a cluster head to establish a 2 or more tiered network architecture. The authors favor hybrid nodes, in this phase of node head election, as they promise to relax bandwith requirements of their cluster using high-throughput FSO antenna.

2.1.3 Free-Space-Optical Interconnects

World-wide internet traffic experienced huge growth in past the few decades. This phenomenal growth created big demand for IP and ATM router and switch products with throughputs of 1Tb/s and beyond. Free-space-optical communication systems

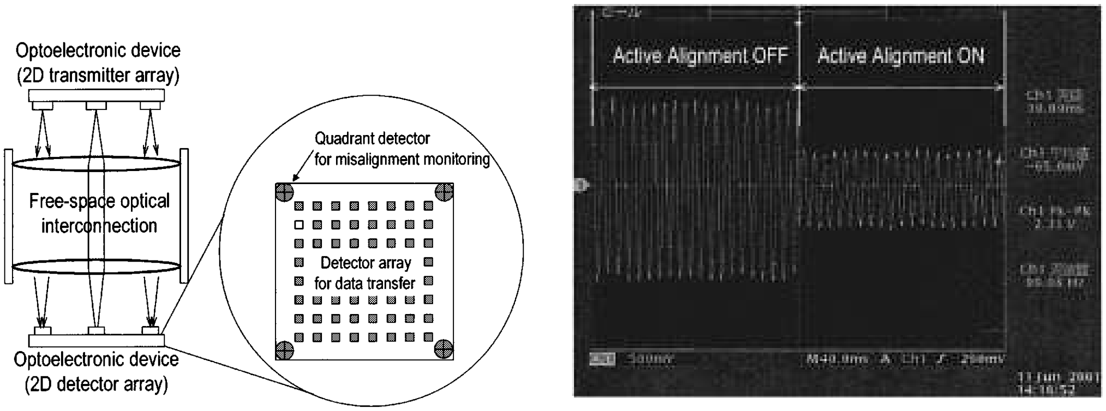


Figure 2.5: FSO interconnect and active alignment demonstration [47]

provide an outstanding alternative to conventional cable based connections required in such large machines to connect frames and racks in big data centers. While optical data rates are quite attractive, there exist problems in such FSO systems deployed in computers:

1. vibration in the environment can easily cause misalignment,
2. parallel deployments can experience cross-talk,
3. proposed solutions may need expensive mechanical instruments like highly precise steering devices.

In this section, we will examine papers that investigate use of FSO technology in interconnects.

Naruse *et al.* investigate a real-time active alignment circuitry for short-distance FSO interconnects to compensate dynamical disturbances [44] (Figure 2.5). The proposed approach solves tight misalignments while preserving spatial density of optical channels. They implemented a piezoelectric microstage and a proportional-integral-derivative control scheme as an experimental system and 118Hz-demonstrations were done. In their design, the misalignment detector arrays play an important role, as they are placed at the peripherals of the parallel data transfer bus channels to detect lateral misalignment error. They, then, use the misalignment signal as a feedback signal for driving the actuator. They also conducted experiments to demonstrate the effectiveness of active alignment, finding that the amplitude of vibration is $10\mu m$ under a 100 Hz mechanical vibration. With the active alignment, fluctuation of misalignment is reduced to $5\mu m$ which poses an attractive solution for misalignment problem in FSO interconnects.

In order to obtain high misalignment tolerances, Bisaillon *et al.* propose an active alignment scheme that uses a redundant set of optical links and active selection of the best link [24]. The authors previously attacked the same problem by placing a large area detector. Their new approach provides a more viable solution since it reduces cross talk between clusters in the case of parallel implementation of such FSO interconnects. Also, they expect better data rates because of the reduced area. They also provide an improved interconnect design to guarantee the efficient source-detector power coupling in desired misalignment tolerance window. They implemented a vertical-cavity surface-emitting laser (VCSEL) and photo-detector (PD) based bi-directional interconnect and examined ranges from 5cm to 25cm with ± 1mm lateral and ± 1° angular misalignment, finding promising results.

Faulkner *et al.* designed a system that uses multi-element antennas to achieve better coverage in an indoor environment [28]. Authors conducted a demo system in a lab environment. They used arrays of laser transmitters and photodiode receivers, and beam-steering optical lenses in between the two. They experimented a solid-state tracking technique that basically selects the best receiver among the photodiodes according to its light intensity. The system is limited in coverage because of low receiver sensitivity. The system also has laser eye-safety issues.

Similarly, Boisset *et al.* [27] designed an active alignment system for FSO interconnects that is based on a quadrand detector and Risley beam steerers. The detector can successfully detect the misalignment error between the center of a spot of light and the center of quadrand detector. Then, this information is fed to an algorithm that calculates rotational displacement required for steerers at both sides. They have conducted experiments that showed that the system is capable of establishing the alignment up to 160 μm of deviation of spot light. They use highly sensitive instruments like step motors in Risley beam steerers which tend to be costly. Researchers have used a single beam that drops on a single photo detector, although the quadrand detector is able to provide the information about beam misalignment.

2.2 Mobile Free-Space-Optical Communications

The key limitation of FSO regarding *mobile* communications is the fact that *LOS alignment must be maintained* for communication to take place successfully. Since the optical beam is highly focused, it is not enough if LOS exists: the transmitter and receiver pair should be aligned; and the alignment must be maintained to compensate for any sway or mobility in the mounting structures. Mobile communication using FSO is considered for indoor environments, within a single room, using diffuse optics technology [17,18,20,25,27,38,47,67], including multi-element transmitter and receiver based antennas. Due to limited power of a single source that is being diffused to spread in all directions, these techniques are suitable for small distances (typically 10s of meters), but not suitable for longer distances.

For outdoors, *fixed* FSO communication techniques have been studied to remedy small vibrations [56, 57], swaying of the buildings have been implemented using mechanical auto-tracking [24, 39, 44] or beam steering [68], and interference [8] and noise [32]. LOS scanning, tracking and alignment have also been studied for years in satellite FSO communications [49, 58]. Again, these works considered long-range links, which utilize very narrow beamwidths (typically in the microradian range), and which typically use slow, bulky beam-scanning devices, such as gimballed telescopes driven by servo motors.

We propose to use electronic scanning/steering techniques by leveraging angular diversity of spherical structures covered with multiple transceivers. We studied such FSO spherical structures and built some of its elementary features such as alignment working at very short distances and very low speeds [11, 69]. These studies showed promising results and we plan to build several fully-structured prototypes of 3-D FSO spheres, which will constitute a lab-based prototype of a demonstrable FSO-MANET working at high speeds and longer communication distances. FSO is very attractive for power-scarce MANET applications such as sensor networks [43]. Though there have been initial attempts (including ours) on using FSO for MANETs [7, 16, 35, 36, 48, 69], an experimental lab demonstration of large-scale FSO-MANET or hybrid RF/FSO-MANET has not been done.

2.3 Effects of Directional Communication on Higher Layers

As discussed earlier, in comparison to RF physical communication characteristics, FSO has critical differences in terms of error behavior, power requirements and different types of hidden node problems. Implications of these physical FSO characteristics on higher layers of the networking stack has been studied in recent years. The majority of the FSO research in higher layers has been on topology construction and maintenance for optical wireless backbone networks [26, 37, 59]. Some work considered dynamic configuration [40], node discovery [60], and hierarchical secure routing [61, 62] in FSO sensor networks. However, no deep investigation of issues and challenges that will be imposed on MANETs by FSO has been performed. In this sense, our work will be the first to explore FSO-MANET research issues relating to routing and data link layers.

A key FSO characteristic that can be leveraged at higher layers is its *directionality* in communication. Though the concept is similar to RF directional antennas, FSO can provide much more accurate estimations of transmission angle by means of its directionality. Previous work (including ours) showed that directionality in communication can be effectively used in localization [12, 41], multi-access control [33, 50], and routing [13, 31, 34, 45, 53]. In addition to directionality, our proposed FSO nodes introduce highly-intermittent disconnectivity pattern (i.e. aligned-misaligned pattern) which affects transport performance [11]. Also, the establishment of an FSO communication link implies that the space between the communicating nodes is Euclidian, which can be leveraged to better design routing and localization protocols. We will explore implications and potential benefits of these properties of directional communication within the context of FSO-MANETs.

R. Choudhury *et al.* explains a simple MAC protocol for directional antennas in [50]. In this research report on directional transmission schemes that is adopted from IEEE 802.11 design, they use a node design that is able to use both omnidirectional and directional transmission modes. A node is able to steer the antenna to point to a desired angle. For the *Simple Directional MAC (DMAC)* approach, they assume that if a node is idle (i.e., there is no ongoing transmission or reception), the node is in omni-directional state. They also implemented RTS and CTS signaling in directional mode. Similar to Network Allocation Vector (NAV) in 802.11, a directional version is introduced (DNAV), which keeps allocation of the time domain and *space domain with a local sense of direction.* Hence, a node looks up entries from this table whenever it needs to send an RTS to a specific direction. Later on, the backoff phase starts.Also, nodes update this table upon receiving an RTS or CTS. However, the hidden terminal problem in 802.11 reveals itself in two other new forms.

- Asymmetric Gain: Since the gain of a directional and omnidirectional antenna under the same power is typically different (i.e., directional gain is greater), sender and receiver nodes with transmit and receive gain 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.
- Unheard RTS/CTS: A node that participates in an ongoing transmission (nodes A and B) will not hear (Figure 2.6) RTS/CTS frames (exchanged with C and D) since its antenna is directed to a specific point. Upon completion of its transmission, any of the two nodes (A and B) pose a potential interference danger to the nodes that are around them (C and D) and that started their transmission while previous nodes were talking to each other.

The authors, then, propose a multi-hop RTS based algorithm (MMAC) to better exploit the greater gain of directional antennas. The protocol is built up on DMAC. Consider a scenario in which A wants to communicate with F, but since they both have directional antennas with greater gain, they want to establish a link in one hop. The first thing A does is to send an RTS directly to F. F may or may not hear this

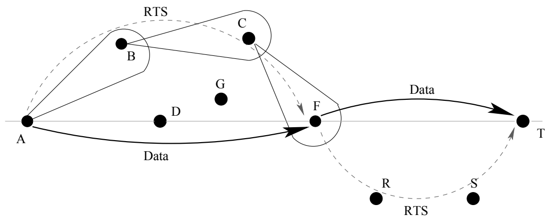


Figure 2.6: Multi-Hop RTS [50]

RTS, most probably will not. A then sends a *multi-hop RTS* destined to F to request F to point its antenna in A's direction, through the multi-hop route A-B-C-F. This RTS is treated in a special way by forwarding nodes. Then A expects a CTS directly from F. This way A can indeed communicate with T. The authors ran simulations of different scenarios to observe the average performance of explained protocols, finding that both protocols perform better than IEEE 802.11, with a dependence on network topology and traffic pattern. This work also provides a motivation for us to better investigate and exploit spatial reuse in our spherical multi-element antenna design. Note that this design uses help of upper layers to route the multi-hop RTS. Also, their design of directional antennas is not capable of utilizing multiple antennas at the same time. Hence, a simple broadcast is achieved by using the antennas sequentially to achieve 360 degree coverage. In our design, multiple transceivers are *intended* to communicate at the same time, yielding simplicity in broadcast operations. Also, this sequential process of transmitters sending out frames will cause operation to span a window of time, instead of being instantaneous and will cause different frames to be timestamped with different values.

In the context of effects of directional antennas on upper layers, R. Choudhury *et al.* evaluates the performance of DSR (Dynamic Source Routing) using directional antennas [53]. They identify issues that emerge from executing DSR (originally designed for omnidirectional antennas) over directional antennas. Specifically, they observe route request (RREQ) floods of DSR are subject to degraded performance due to directional transmission is not covering as much space as omnidirectional transmission, resulting route reply (RREP) to take longer time. Also, they observed that using directional antennas may not be suitable when the network is dense or linear, because of increased interference. However, the improvement in performance may be encouraging for networks with sparse and random topologies. Note that both simulations are conducted using CBR (Constant Bit Rate), on top of UDP; they do not present any results related to TCP. Additionally, found performance boosts are subject to a specific network topology and traffic pattern.

Chapter 3

Free-Space-Optics Basics and NS-2 Contribution

In this chapter, we delve into the details of free-space-optical communication technology, propagation model used in our simulations and interface alignment [66].

3.1 FSO Propagation Model

The important difference between a fiber-optical and free-space-optical link is the lack of a reliable medium for the propagation of light. This poses an important challenge for FSO, since the medium can change significantly over time. To tolerate adverse effects of water vapor, carbon dioxide, ozone and etc. the designer of a FSO system must be aware of of losses in the system. We will describe dominant system characteristics of FSO to be able to derive such system losses. For sake of simplicity we neglect any optical losses since we do not use any optical lenses in our design.

3.1.1 Geometrical Loss

Geometrical loss counts for the losses that occur due to the divergence of the optical beam (Figure 3.1). The result of divergence is that some or most of the beam is not collected at the receiving side. The loss can be roughly sketched as the area of receiver relative to the area of the beam at receiver. We can accurately assume that the cone formed by the beam is in the shape of a linear rectangle. If we measure the diameters in *cm*, the distance in *km* and the divergence in *mrad*, the formula becomes as follows:

$$\frac{A_R}{A_B} = \Big(\frac{D_R}{D_T + 100 * d * \theta}\Big)^2$$

in which abbreviated parameters are as follows:

Parameter Descriptions	
A_R	Area of the receiver
A_B	Area of the beam
D_R	Diameter of the receiver at receiver
D_T	Diameter of the transmitter
d	Separation of transmitter and receiver
θ	Divergence angle

3.1.2 Atmospheric Loss

The atmosphere causes signal degradation and attenuation in a free-space system link in several ways, including absorption, scattering (mainly modeled as Mie scattering), and scillintation. All those effects vary in time and basically depend on the condition of the weather. The atmospheric attenuation A_L consists of absorption and scattering

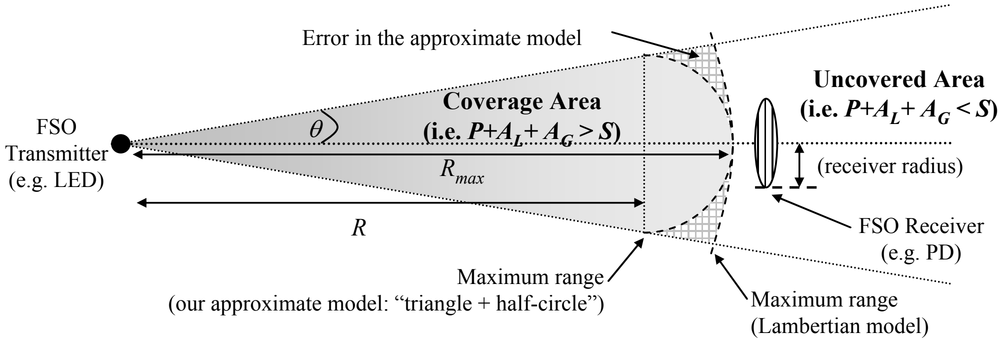


Figure 3.1: Light intensity profile of an optical beam.

of the laser light photons by the different aerosols and gaseous molecules in the atmosphere. The power loss due to atmospheric propagation is given by Bragg's Law [66] as:

$$A_L = 10\log(e^{-\sigma R})$$

where σ is the attenuation coefficient consisting of atmospheric absorption and scattering. Mie scattering occurs because of the particles that are about the size of beam wavelength. Therefore, in the near infrared wavelength range, fog, haze, and pollution caused by the aerosols, are the major contributors to the Mie scattering effect. There are also scattering models, but for the wavelengths used for FSO communication, Mie scattering dominates the other losses, and therefore is given by [65, 66]:

$$\sigma = \frac{3.91}{V}\left(\frac{\lambda}{550}\right)^{-q}.$$

In the above formulation of σ, V is the atmospheric visibility in kilometers, q is the size distribution of the scattering particles whose value is dependent on the

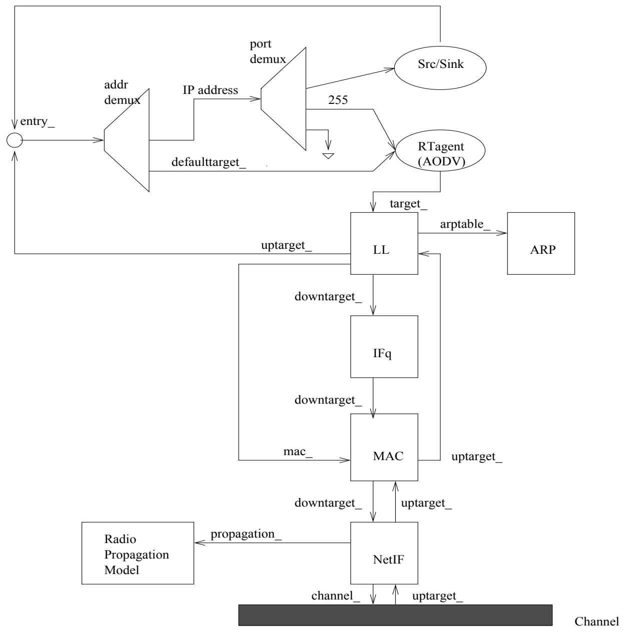


Figure 3.2: Internal design of a wireless node in NS-2. [3]

visibility:

$$q = \begin{cases} 1.6 & V \geq 50\text{km} \\ 1.3 & 6\text{km} \leq V < 50\text{km} \\ 0.583V^{1/3} & V < 6\text{km} \end{cases}$$

The above losses and receiver sensitivity threshold must be taken into account for calculation of the link margin.

3.2 Interface Alignment Implementation in NS-2

Our interface alignment implementation gradually evolved. This section will focus on the initial implementation and introduced improvements later on. First version of this alignment detection code was originally implemented in [23].

3.2.1 Initial Alignment Implementation and Enhancements

This first implementation was placed in NS to cover urgent needs of researchers. The code that determined alignment of two interfaces was placed in *channel.cc*. Hence, the channel was kept responsible for determining which interfaces in the network will receive a packet that is handed to *channel* (Figure 3.2).

The logical flow was as follows (only details that are relevant to alignment are included, leaving everthing else excluded for simplicity reasons) :

1. A packet is given from MAC (i.e., *mac-802_11.cc*) to *wireless-phy.cc*
2. *wireless-phy.cc* hands the packet to *channel.cc*
3. *channel.cc* extracts the meta data information, that is put in the packet headers to determine the divergence angle, specific position and normal of the sending transceiver.
4. *channel.cc* goes through every node in the network, to find out if the sender transceiver can see the candidate node (based on center of the node), and if one of the transceivers on the candidate node can see the sender node.
5. If the two given nodes can see each other, *channel.cc* schedules a reception for each transceiver in the candidate node. Hence, each transceiver receives a copy of the packet and delivers it to the upper layers.

As the first enhancement, we changed the above procedure such that; *channel.cc* goes through every transceiver in the network, to find out if the sender transceiver and the candidate transceiver can *see* each other, i.e., they are in one another's line of sight. Note that, this way of determining alignment based on the position of transceivers is more accurate since the center of the node and coordinates of a transceiver can be considerably apart from each other based on the diameter of the node. For small nodes, this does not pose a problem but for nodes with 10 cm or bigger diameter, this affects the alignment accuracy. Then, if the two given transceivers can see each other, *channel.cc* schedules a reception: the receiving transceiver is the candidate transceiver, that was just examined and the packet is the packet that the *channel.cc* was handed.

This procedure was executed every time a packet is given to the channel. Note that, although it is not impossible to design the auto-alignment circuit in such a way that two transceivers exchange search signals every time a packet is going to be sent, it does not adhere to the initial design of the auto-alignment circuit. The basic principle in the design of auto-alignment circuit is that search signals are sent from a transceiver in periodic times, e.g., every second. So that, according to the received responses, a transceiver can keep track of its aligned neighbors.

Also, note that the alignment is conservatively determined mutually. Thus, for two interfaces to be considered as *aligned*, both must see each other; if one of them sees the other, then the alignment is not considered as established. Although partial alignment would be a perfectly acceptable improvement, we made our design decisions conservatively.

3.2.2 Timer-Based Alignment Implementation

According to the principal idea in auto-alignment circuitry, we decided to implement interface alignment procedure periodically instead of every time a packet is sent. As the second enhancement, we introduced a MAC level timer. This timer goes off with a predetermined (roughly, 0.5 sec) frequency and calculate the alignments in

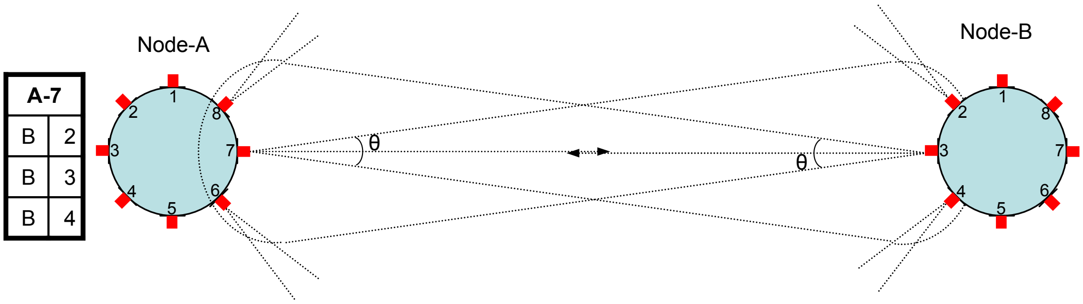


Figure 3.3: Multi-element antenna design in 2D view and sample alignment table kept in interface 7 of node A.

the network. Since every interface has its own MAC layer, it also has a alignment timer (code name *AlingmentTimer*). Practically, the resulting design is that every transceiver determines its aligned neighbor and keeps a table that has an entry for each aligned transceiver.

As illustrated in Figure 3.3, interface 7 on node A (named *A-7*) has an alignment table and its entries are *B-2, B-3* and *B-4*. Identically, every transceiver in the network keeps a table like this to keep track of its aligned neighboring transceivers. In this design, whenever a packet is being sent, the channel determines alignments based on this alignment table. The channel looks at the entries of alignment table and does a secondary check to see if the two interfaces are still aligned (two way alignment check). If they are still aligned, the channel delivers the packet to the receiving transceiver. If they are not aligned, the channel quietly purges the packet. This model is not only computationally more relaxing, but also more realistic from auto-alignment circuit's point of view.

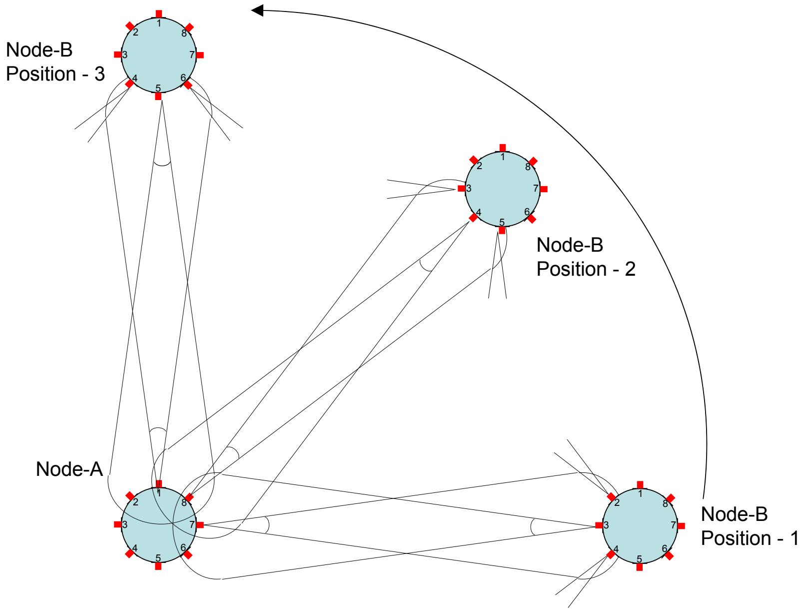


Figure 3.4: Sample alignment scenario for two mobile nodes.

3.3 Alignment Scenarios and Mobile Node Design

Directionality of FSO antennas causes alignment and misalignment pattern to repeat frequently in mobile scenarios. Consider a scenario with two nodes: Node-A and Node-B (Figure 3.4). While Node-A stays stationary, Node-B moves with an arc route from Position-1 to Position-3 as illustrated. In this scenario, the two nodes loose their alignment while Node-B is in intermediate states, i.e., between postions 1 and 2 and between 2 and 3.

Choosing the divergence angle and number of transceivers in the node are two important parameters that effect intermittency of the connection between two nodes. Such a choice should optimize a number of metrics: reduce the interference area that is created by two adjacent transceivers and increase overall coverage area. Also, putting more transceivers is good for spatial reuse, but effects throughput badly for

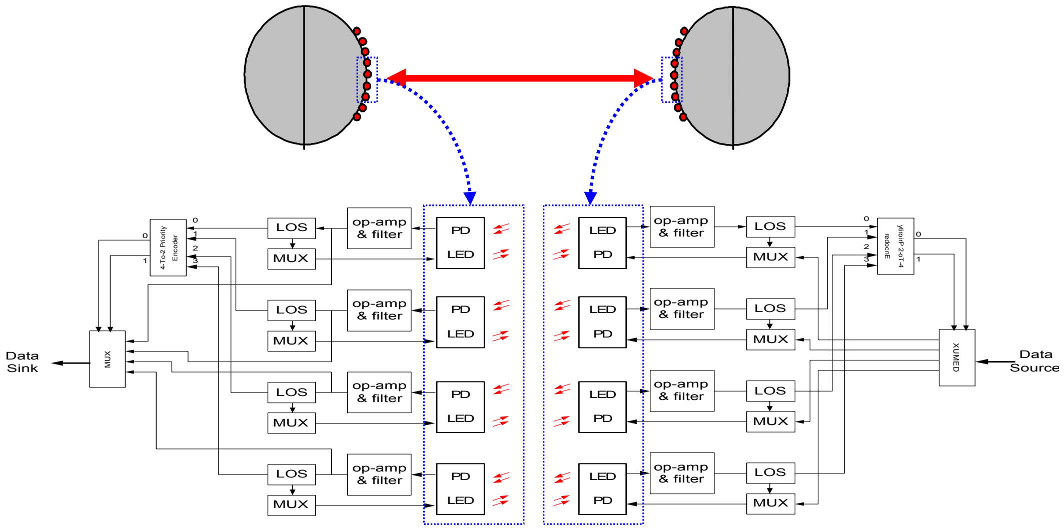


Figure 3.5: Schematic of the auto-alignment circuitry.

mobile cases. Those system parameters and their implications are examined in depth by Yuksel *et al.* in [69]. We adhere to the designs proposed by Yuksel *et al.* and base our simulations on those indoor and outdoor designs (Tables 3 and 4 in [69]).

3.4 Auto-Alignment Circuitry

Yuksel *et al.* designed an alignment circuitry to remedy the problem of hand-off [69]. Note that as two nodes are mobile with respect to each other, they will be loosing and re-gaining their alignments with each other. And, the specific transceivers used for communication in both nodes should be changed as the nodes move. Auto-alignment circuitry, contrary to mechanical steering mechanism, delivers quick and auto hand-off of logical flows among different transceivers.

Alignment is detected in a two-phased fashion [11]: Whenever the light intensity drops under a predefined threshold, the search phase begins to re-establish the alignment. In the event of misalignment, the transceiver first sends a pilot search signal (e.g., 1010110), which is commonly known among all nodes in the network. If the transceiver receives the same input as the search signal, then it determines that LOS is available and the alignment is established. Once LOS alignment is established the structure selects this transceiver as the one that needs to send data and the second phase is entered. The key idea is that two nearby spheres, which lost alignment due to mobility, will eventually receive the search signals upon existence of a new LOS.

In the mobility scenario that we illustrated in Figure 3.4, auto-alignment circuitry in Node-A for instance, will successfully switch from *interface 7* to *8* and finally to *1* as Node-B changes its position from *Position-1* to *Position-2* and *Position-3*; thus *handing-off* the logical stream to a different physical channel, i.e., transceiver. Ideally, this selection of specific transceiver to carry a logical flow (e.g., an FTP session) and the switching between different transceivers should be transparent to the upper layers.

Chapter 4

Effects of Multi-Element FSO Structures on Higher Layers

This chapter exposes the details of our simulation scenarios, their implementation details, results and findings from these simulations. Simulations are designed to specifically pinpoint various aspects of free-space-optical communication via multi-element optical antennas. We first explain the common parameter set and implementation details of our simulations. On this common stage, we give altered parameters or algorithmic details for every simulation set. After presenting the results, we conclude our ideas on the experiment and describe possible other scenarios or modifications to the current one for further investigation.

We implemented our simulations using the well-recognized network simulation tool NS-2 (Network Simulator - 2 [3]). This simulation system allows researchers to freely implement modular pieces of the system like queues, antennas, etc. since the system is open source. NS-2 comes as a package, including various off-the-shelf components to simulate large scale contemporary networks and various utilities to

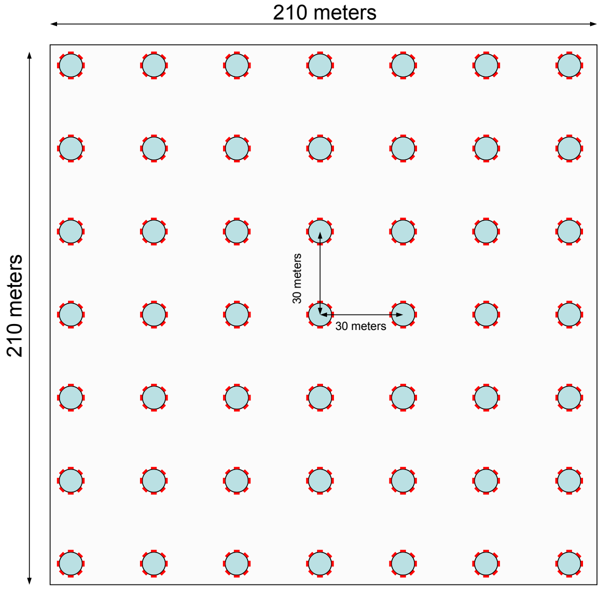


Figure 4.1: Initial positioning of nodes.

help the researchers. Among the utilities that were beneficial to us are *setdest* and *threshold*. We used *setdest* to generate mobility movement patterns of individual nodes and *threshold* to calculate the sensitivity threshold value for RF antennas.

The architecture of NS-2 is composed of three main components: interpreted code written in TCL language (a scripting language, hence, no strict type checking), native code written in C/C++ and an interpreter mechanism that bridges the two components. Typically, simulation definition files are implemented in TCL code. We wrote code that spans both parts of the system; propagation model in C/C++ and simulations and other helper code in TCL.

The network design that we adhered while implementing most of the simulation scenarios is common. Those values indicated here are valid if specific values are not provided. In stationary simulations where there is no mobility, nodes are placed on a $210m$ by $210m$ area as a 7 by 7 node grid; 49 nodes in total. Separation of nodes is

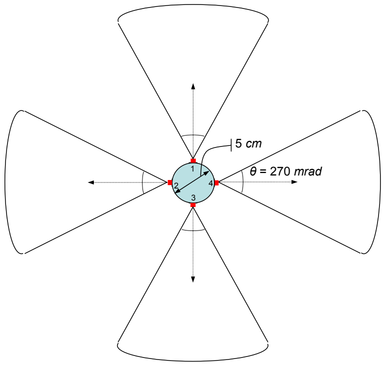
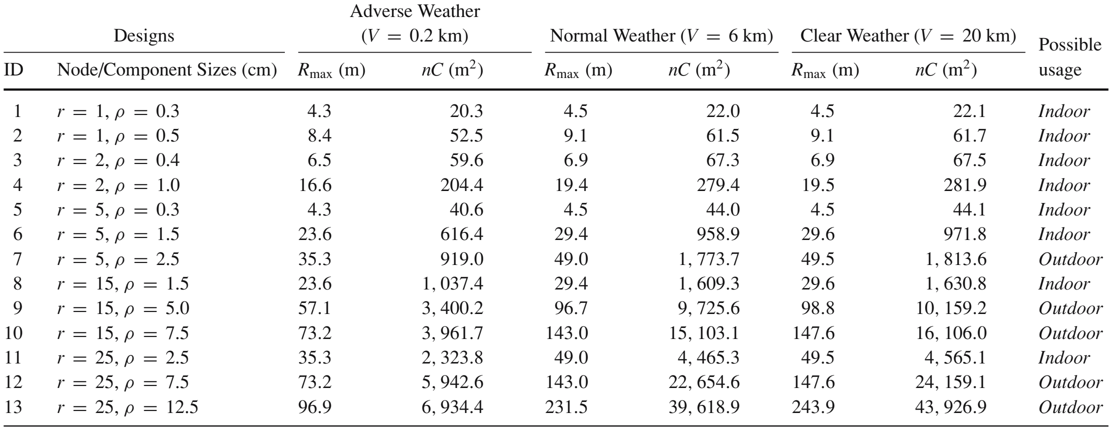


Figure 4.2: Typical FSO node with 4 interfaces.

30 meters (Figure 4.1). In stationary scenarios, all the nodes in the network preserve their position until the simulation finishes. Common mobility parameter is 0.1 m/s; that is, all the nodes in the network move with a speed of 0.1 m/s according to a random waypoint algorithm. The mobility behavior of the nodes is determined by a *mobility scenario file* that is generated by the standard utility program named *setdest* (abbreviation of set destination) that comes with the NS-2 package. Note that it is a well-known fact that in real-life mobility scenarios most of the nodes in the network have no or little amount of mobility (0.1 $m/s - 1$ m/s), while a significantly small portion of the nodes ($\%1-\%10$) move with higher speeds. In the mobile scenarios, the nodes in the network are positioned according to the same 7 by 7 grid configuration before the simulation starts.

The transmit range of an individual transceivers is $30m$. The necessary power to reach 30 meters for FSO nodes is calculated in *fso-util.tcl*. Similarly for RF, we calculated required power and thereshold value using *threshold*. In our common node design, there are 4 transceivers as illustrated in Figure 4.2. The divergence angle of each transceiver is 270 $mrad$. Each interface has its own MAC implementation and, thus, is connected to the network layer separately and represents an fully operational



Designs		Adverse Weather ($V = 0.2$ km)		Normal Weather ($V = 6$ km)		Clear Weather ($V = 20$ km)		Possible usage
ID	Node/Component Sizes (cm)	$R_{\max}$ (m)	nC (m^2)	$R_{\max}$ (m)	nC (m^2)	$R_{\max}$ (m)	nC (m^2)	
1	$r = 1, \rho = 0.3$	4.3	20.3	4.5	22.0	4.5	22.1	*Indoor*
2	$r = 1, \rho = 0.5$	8.4	52.5	9.1	61.5	9.1	61.7	*Indoor*
3	$r = 2, \rho = 0.4$	6.5	59.6	6.9	67.3	6.9	67.5	*Indoor*
4	$r = 2, \rho = 1.0$	16.6	204.4	19.4	279.4	19.5	281.9	*Indoor*
5	$r = 5, \rho = 0.3$	4.3	40.6	4.5	44.0	4.5	44.1	*Indoor*
6	$r = 5, \rho = 1.5$	23.6	616.4	29.4	958.9	29.6	971.8	*Indoor*
7	$r = 5, \rho = 2.5$	35.3	919.0	49.0	1, 773.7	49.5	1, 813.6	*Outdoor*
8	$r = 15, \rho = 1.5$	23.6	1, 037.4	29.4	1, 609.3	29.6	1, 630.8	*Indoor*
9	$r = 15, \rho = 5.0$	57.1	3, 400.2	96.7	9, 725.6	98.8	10, 159.2	*Outdoor*
10	$r = 15, \rho = 7.5$	73.2	3, 961.7	143.0	15, 103.1	147.6	16, 106.0	*Outdoor*
11	$r = 25, \rho = 2.5$	35.3	2, 323.8	49.0	4, 465.3	49.5	4, 565.1	*Indoor*
12	$r = 25, \rho = 7.5$	73.2	5, 942.6	143.0	22, 654.6	147.6	24, 159.1	*Outdoor*
13	$r = 25, \rho = 12.5$	96.9	6, 934.4	231.5	39, 618.9	243.9	43, 926.9	*Outdoor*

Figure 4.3: Table 3: Indoor and outdoor FSO node designs with $\theta = 200\ mrad$ given in [69].

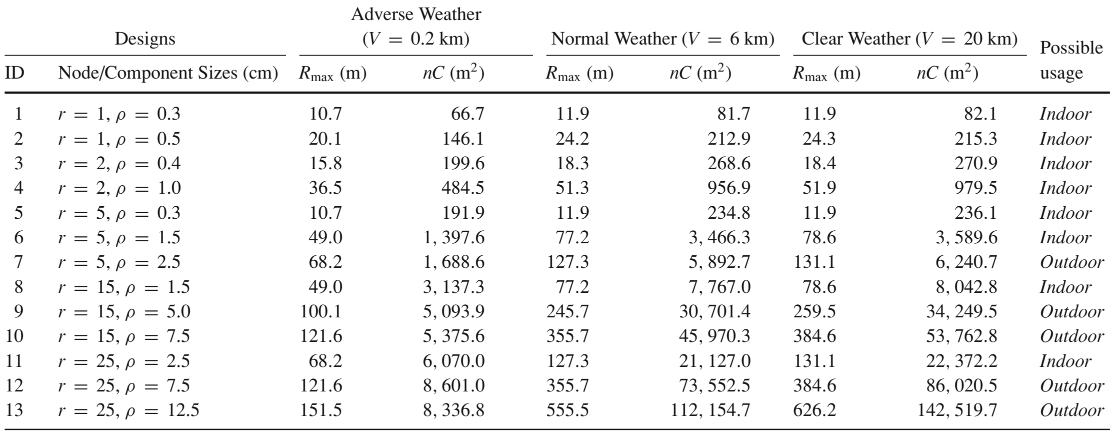
optical link.

We designed simulations to run 3000 seconds, which is an enough amount of time to grasp the overall network behavior. The diameter of a circular FSO node is 5 *cm*. We simulated the transmitter and receiver as attached to each other. The diameter of a transmitter is 2.5 *cm* and the diameter of a receiver is 0.5 *cm*. Separate simulation sets will keep all those default values unchanged but will alter one parameter; conducting a controlled experiment. We will explain the changed parameter and its effect on overall system throughput in the following sections.

4.1 Analysis of FSO Behavior

4.1.1 Basic Simulation Set for FSO

We simulated a subset of various indoor and outdoor node designs presented in Table 3 and Table 4 (Figures 4.3 and 4.4) in [69]. While all of the node designs yield



Designs		Adverse Weather ($V = 0.2$ km)		Normal Weather ($V = 6$ km)		Clear Weather ($V = 20$ km)		Possible usage
ID	Node/Component Sizes (cm)	$R_{\max}$ (m)	nC (m^2)	$R_{\max}$ (m)	nC (m^2)	$R_{\max}$ (m)	nC (m^2)	
1	$r = 1, \rho = 0.3$	10.7	66.7	11.9	81.7	11.9	82.1	*Indoor*
2	$r = 1, \rho = 0.5$	20.1	146.1	24.2	212.9	24.3	215.3	*Indoor*
3	$r = 2, \rho = 0.4$	15.8	199.6	18.3	268.6	18.4	270.9	*Indoor*
4	$r = 2, \rho = 1.0$	36.5	484.5	51.3	956.9	51.9	979.5	*Indoor*
5	$r = 5, \rho = 0.3$	10.7	191.9	11.9	234.8	11.9	236.1	*Indoor*
6	$r = 5, \rho = 1.5$	49.0	1, 397.6	77.2	3, 466.3	78.6	3, 589.6	*Indoor*
7	$r = 5, \rho = 2.5$	68.2	1, 688.6	127.3	5, 892.7	131.1	6, 240.7	*Outdoor*
8	$r = 15, \rho = 1.5$	49.0	3, 137.3	77.2	7, 767.0	78.6	8, 042.8	*Indoor*
9	$r = 15, \rho = 5.0$	100.1	5, 093.9	245.7	30, 701.4	259.5	34, 249.5	*Outdoor*
10	$r = 15, \rho = 7.5$	121.6	5, 375.6	355.7	45, 970.3	384.6	53, 762.8	*Outdoor*
11	$r = 25, \rho = 2.5$	68.2	6, 070.0	127.3	21, 127.0	131.1	22, 372.2	*Indoor*
12	$r = 25, \rho = 7.5$	121.6	8, 601.0	355.7	73, 552.5	384.6	86, 020.5	*Outdoor*
13	$r = 25, \rho = 12.5$	151.5	8, 336.8	555.5	112, 154.7	626.2	142, 519.7	*Outdoor*

Figure 4.4: Table 3 and 4: Indoor and outdoor FSO node designs with $\theta = 75$ $mrad$ given in [69].

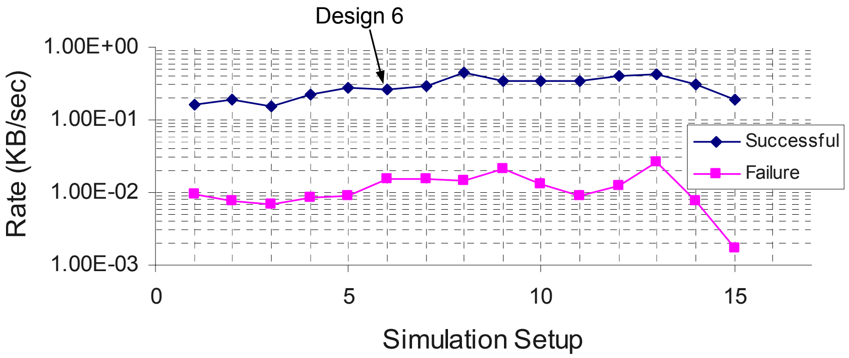


Figure 4.5: Comparison of basic node designs from Table 3 and Table 4 of [69].

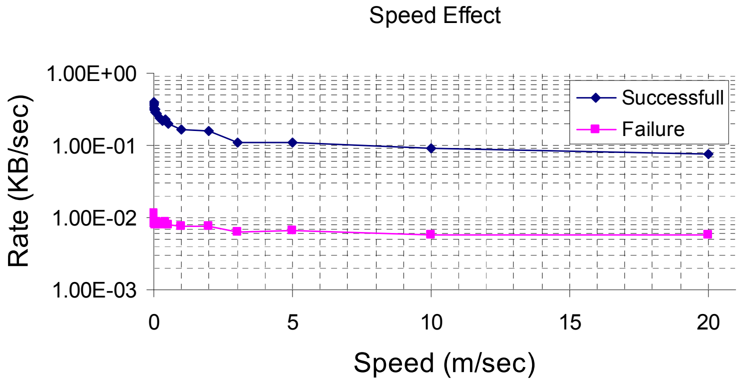


Figure 4.6: Mobility effect on FSO.

to high throughput, we found that some of them perform better. Among those outstanding ones, we preferred a modest and simple design as our skeleton in most of the simulations. This design has 4 interfaces and the divergence angle is 270 $mrad$ (illustrated in Figure 4.5, 7^{th} entry in Table 3).

4.1.2 Speed Effect and Intermittent Connectivity Nature of FSO

Analysis of speed effect on free-space-optical networks poses a significant importance for our research. This is mainly because there exists no effort in the history of free-space-optical communication that even considers FSO as a mobile ad hoc networking style. Researchers have designed hybrid (FSO/RF) systems in which FSO is mainly considered as a complimentary technology that often functions as a backbone to solve the problem of vanishing end-to-end throughput of RF systems.

However, we designed and successfully simulated and partially implemented (lab colleague Thaison Dao) such pure-FSO mobile ad hoc networks that can han-

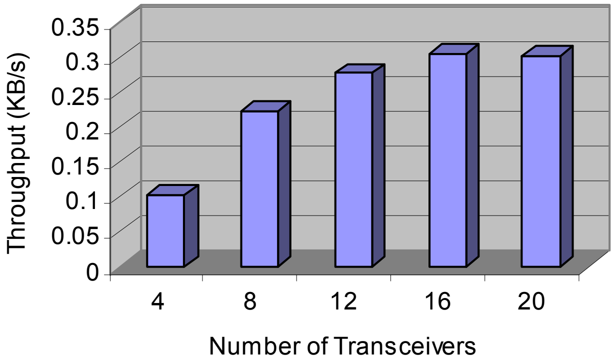


Figure 4.7: Effect of number of transceivers on throughput.

dle mobility with the help of a multi-element optical antenna design and an auto-alignment circuitry. We observed that although mobility is not impossible, it degrades the system performance in terms of throughput in such a way that it practically forces us to review of design decisions of higher layers in the TCP/IP stack. We conclude that performance of TCP is adversely effected from the *intermittent connectivity pattern* which becomes more dominant when mobility is increased.

To interpret the simulation results that we illustrated in Figure 4.6; multi-element node design enables spatial reuse which provides better channel usage by letting simultaneous access to the underlying physical channel. This advantage tends to provide lesser gain and in fact cause a coverage issue when high mobility is introduced. Because of this coverage problem, per-node throughput drops significantly as the mobility approaches to 20 m/s level.

Although mobility is a challenge for FSO networks, we saw that optical communication performs better than omni-directional RF because of angular diversity and spatial reuse (see next section) and we can remedy this challenge of intermittent connectivity by employing directional MAC and additional buffers and make this fundamentally different error behavior of the underlying channel *transparent* to higher layers. We explain specific details in Chapter 5.

4.1.3 Transceiver Effect and Spatial Reuse

With using multi-element directional antennas, we exploited the benefits of angular diversity and spatial reuse. We found out that increased number of transceivers generally yield to better channel usage and increased end-to-end throughput. We conducted both stationary and mobile simulations to depict the effect of number of transceivers in both cases. Our research reveals that marginal throughput gain from an additional transceiver decreases as interference becomes more effective since intersection area of two adjacent transceivers becomes less negligible. Thus, we saw a gentle drop in throughput in our simulations after 16 transceivers (Figure 4.7) for the default node design that we discussed earlier.

4.1.4 User Datagram Protocol (UDP) Simulations

Our conclusion is backed by UDP simulations that show the performance loss when TCP is used. In these UDP simulations, we replaced TCP agent with a UDP agent. Because UDP is not affected from the intermittent connectivity of the underlying physical link, its overall throughput is better when compared to TCP.

4.1.5 Divergence Angle Experiments

We increased divergence angle from 2.5 *mrad* to 300 *mrad* and adjusted number of transceivers and LED and photo-detector diameter accordingly. We found out that after a point throughput of the system does not increase too much. We conclude

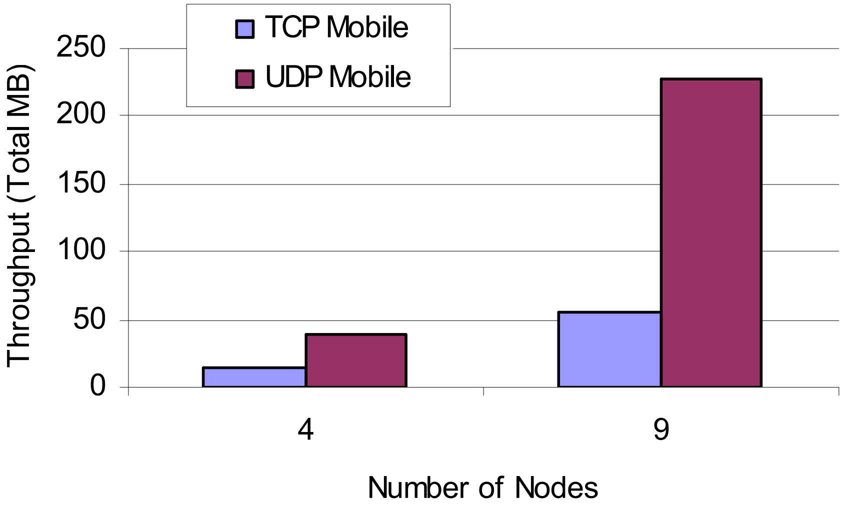


Figure 4.8: User datagram protocol simulation results.

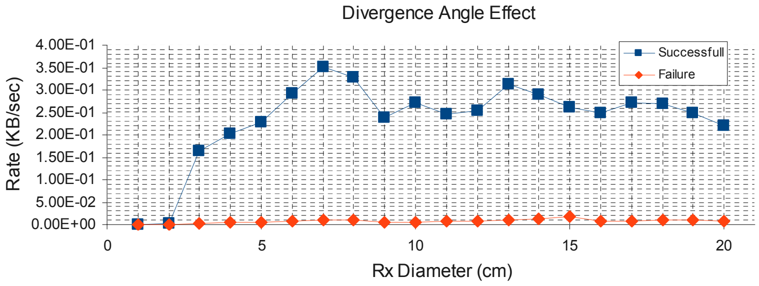


Figure 4.9: Effect of increased divergence angle.

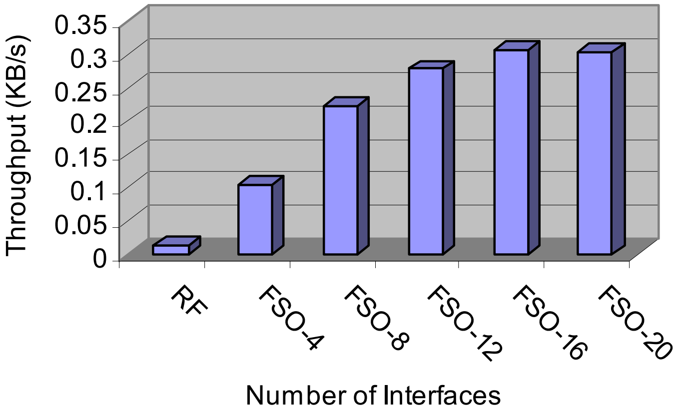


Figure 4.10: Stationary FSO and RF comparison.

that this is because increased interference caused by the wide divergence angle of transceivers.

4.2 Comparison of FSO with RF

4.2.1 Stationary Case

This simulation set is ran in a $280m$ by $280m$ area where the separation between nodes is $40m$. We compared RF and FSO, and experimented FSO with different number of transceivers. We found that FSO performs multiple times better that RF when compared in a stationary setup in which nodes are not moving. Moreover, FSO has the potential to provide better throughput when the number of interfaces on an FSO node is increased from 4 to 20.

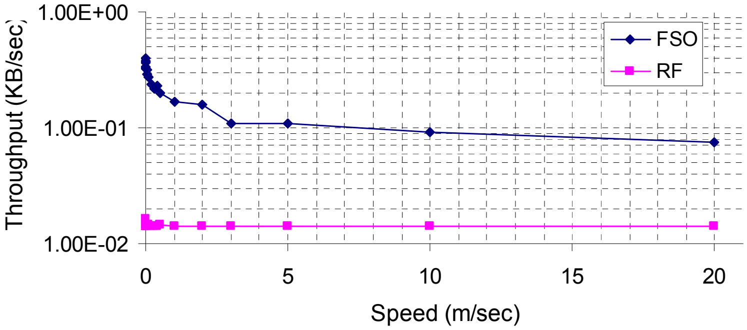


Figure 4.11: Mobile FSO and RF comparison.

4.2.2 Mobile Case

We ran mobile simulations of FSO and RF using the default configuration of system parameters. To present an apples-to-apples comparison, we calculated the required power for both FSO and RF so that they are able to reach an *equal transmission range* (i.e., 30 meters). We gradually increased the mobility of the nodes in the system. Our findings are; when mobility is introduced, overall system throughput drops dramatically for FSO. But RF does not seem to be as adversely effected as FSO. RF behaves very linearly and does not react seriously to the mobility. We conclude that this behavior of FSO is because of the *intermittent connectivity pattern of FSO* and since RF is uses omni-directional frequency, the channel may fade in time but there is no complete disconnection in RF transmission. In fact, RF never experiences channel fading, because the simulated area is practically flat.

4.2.3 Node Density with Adjusted Power

Another simulation scenario (Figure 4.12) adjusts the transmission power of both FSO and RF while expanding the simulation area. The transmission power is adjusted such

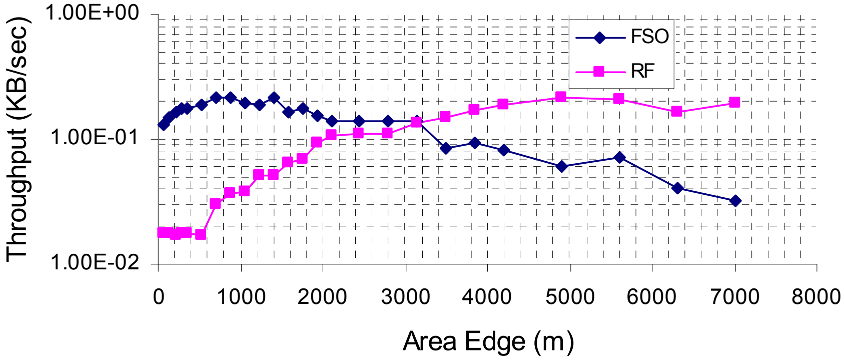


Figure 4.12: FSO - RF comparison: Node density analysis with adjusted power.

that each node can establish 1% BER communication links to its immediate neighbor, regardless of the distance between the nodes. This means that RF nodes will have to spend significantly more transmission power to keep their BER at 1%. In this scenario, simulation area is changed from 70m×70m to 7km×7km. For scenarios in which the area edge is less than 2km, FSO performs better than RF. They converge to a common throughput at 2km and RF starts to perform better than FSO after this point. This is due to the fact that there are more uncovered areas in the case of FSO. Though we are not showing the power consumption results, RF spends a lot more power to maintain the communication links to immediate neighbors. So, FSO is still performing better in terms of throughput per power.

4.2.4 Node Density with Fixed Power

Figure 4.13 shows results of a simulation set in which we kept the transmission power and all other parameters the same, while expanding the modeled area from 70m×70m up to 14km×14km. From the graph, we can conclude that overall throughput of both

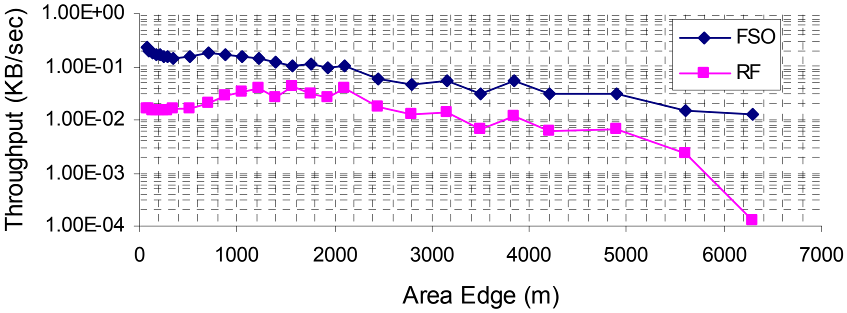


Figure 4.13: FSO - RF comparison: Node density analysis with fixed power.

FSO and RF drop severely since the power is not adjusted accordingly.

Chapter 5

Conclusions and Future Work

Free-space-optical communication via multi-element antennas has an attractive potential towards being used as the next generation wireless communication technology because of its high speed modulation capability where RF networks suffer from a vanishing end-to-end throughput caused by spectral saturations. Our research revealed that FSO can perform multiple times better that RF because of a multi-element optical antenna design that exploits spatial reuse. We presented the results of our simulations and observed that intermittent connectivity pattern of FSO nodes cause the transport-level end-to-end throughput to drop severely. This problem of degrading throughput can be increased by introducing enhancements to the TCP/IP stack. Moreover, the two technologies are in fact complementary to each other. In a hybrid environment where nodes accommodate both RF and FSO capabilities and a suitable network stack that can take advantage of both technologies, RF can overcome FSO's coverage issues while FSO can meet high-bandwidth requirements of the network..

To suppress this frequent failure of underlying link, we plan to design a link layer or higher layer mechanism to buffer the packets in the event of a misalignment.

Once an interface or a set of interfaces detects that it lost it all alignment, it can buffer packets that it received from upper layers until it re-establishes the connection. Additionally, we plan to associate interfaces with *groups*. For instance, if there are 20 interfaces placed on a node, there can be 4 groups with 5 adjacent interfaces in each group. In this case of dense packaging of transceivers, we can design per-group buffers, i.e., a group of interfaces shares a buffer, possibly with a larger capacity. Thus, handing-off a logical stream among different interfaces in the same group would be accomplished without any packet loss. Moreover, the buffering mechanism can be implemented on higher layers to enable collaboration of groups of transceivers and a combination of those buffers can be used as well. In such scenarios, a cross layer design will be needed to take advantage of the buffers at different layers.

Directional antennas have less power consumption while omni-directional antennas need more power to send the signal in all directions. We plan to conduct research that identifies the differences in power usage of free-space optical and radio frequency based wireless communication systems. Such an analysis would discover possibility of FSO MANETs with power constraints, making FSO even more attractive compared to RF MANETs.

The highly directional nature of the beam makes FSO a promising technology for localization as well. We will incorporate directional MAC [53] and provide this valuable information to upper layers to establish location-awareness and make usage of location-based routing protocols possible.

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