Building Blocks for Mobile Free-Space-Optical Networks

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Abstract- **Existence of line of sight (LOS) and alignment between the communicating antennas are one of the key requirements for free-space-optical (FSO) communication. To ensure uninterrupted data flow, auto-aligning transmitter and receiver modules are necessary. We propose a new optical antenna design that employs spherical antennas covered with transmitter and receiver modules for maintaining optical links even when antennas are in relative motion.**

In this paper, for proof-of-concept, we design and test an auto-configurable circuit integrated with light sources and detectors placed on spherical surfaces. We also perform simulation-based analysis of these multi-element FSO modules that can enable mobility and high bandwidth in wireless, particularly indoor, networks. Broader impact of our work is to make FSO communication technology widely applicable in mobile, ad-hoc, and multi-hop wireless networks.

I. INTRODUCTION

Optical wireless , also known as free space optics (FSO), is an effective high bandwidth communication technology serving commercial point-to-point links in terrestrial last mile applications [4][5][6][10][11][12] and in infrared indoor LANs [7][8]. FSO has several attractive characteristics such as (i) *dense spatial reuse*, (ii) *low power usage per transmitted bit*, (iii) *license-free band of operation*, and (iv) *relatively high bandwidth*. Despite these features it has not been considered as a communication environment for general-purpose metropolitan area networks or multi-hop ad-hoc networks, which are currently based on radio frequency (RF) communication technologies [1][2][3]. The reasons are inherent to FSO environment: (i) need for the existence of line of sight (LOS) alignment between communicating nodes, (ii) need for continuous adjustment to maintain LOS, and (iii) reduced transmission quality in adverse weather conditions [12][9].

In this paper, we attempt to answer the question whether or not FSO communications will provide better than existing capabilities for mobile ad hoc wireless networks by means of novel optical antenna building blocks. In order to enable FSO communication in *mobile* environments, we introduce the concept of spherical optical antenna that provides *angular diversity* and hence LOS in 3-dimensions. We also employ *spatial reuse* by tessellating multiple optical transceivers on the surface of a sphere. The tessellation not only improves the range characteristics because every direction now has an inexpensive light source (e.g. LEDs) whose operating range is typically a few hundred meters, but also enables multi-channel simultaneous communication through each transceiver.

Another significant advantage of high resolution tessellation on spherical surfaces is that it allows electronic tracking of the light beam coming from a mobile peer. We designed an auto-alignment circuit that monitors the LOS between two communicating spherical optical antennas, and latches automatically onto existing LOS points, i.e. it electronically tracks the light beams to maintain continuous LOS even when the antennas are mobile, and demonstrated the mobility in a two-node proto-type experiment. To the best of our knowledge, *this is the first time spatial and angular diversity coupled with electronic tracking for mobile communications using FSO* is being reported.

Also, we analyze effectiveness of FSO communication in mobile environments through simulation experiments in NS-2 [13]. To facilitate this, we develop and implement an FSO propagation model and other necessary simulation components (e.g. mobile FSO antennas) in NS-2 environment. The key differentiator is that in the past FSO simulations only included physical layer dynamics; whereas we include all dynamics involved in layers up to 4: optical propagation of Layer 1, auto-configuration/alignment of Layer 2, and transport issues of Layer 4. Then using these simulation models and components, we simulate various mobility scenarios for FSO networks. We show through simulation that dense spatial integration of inexpensive optical components on spherical nodes can provide spatial diversity necessary for reliable optical connectivity.

The rest of the paper is organized as follows: First in Section II, we survey the research on FSO communications. We present our novel design of auto-aligning spherical optical antenna in Section III, along with an experimental demonstration. Then, in Section IIV, we present details of our simulation models for FSO nodes in the open-source network simulator NS-2. In Section V, we validate our simulation components and present simulation results. Finally, we conclude by a brief summary in Section VI.

II. BACKGROUND

Mobile communication using FSO is considered for indoor environments, within a single room, using *diffuse optics* technology [5][15][16]. 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,

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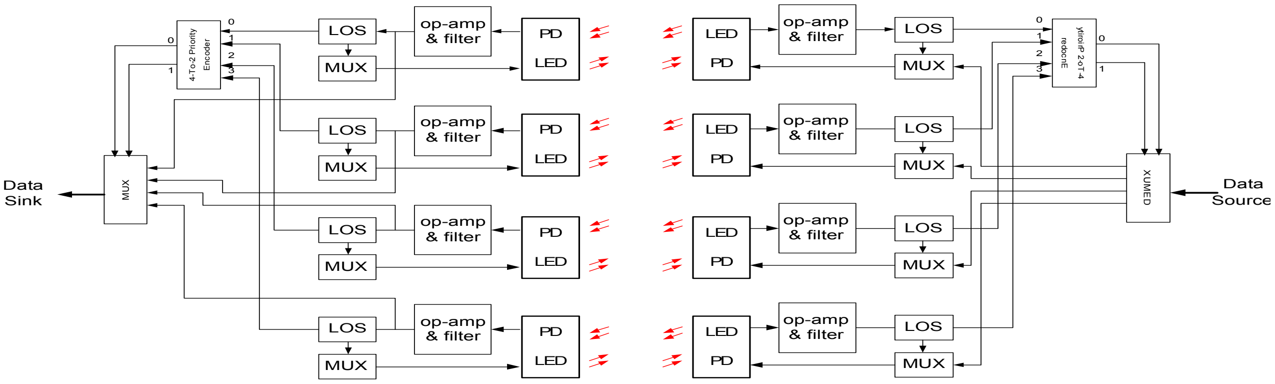
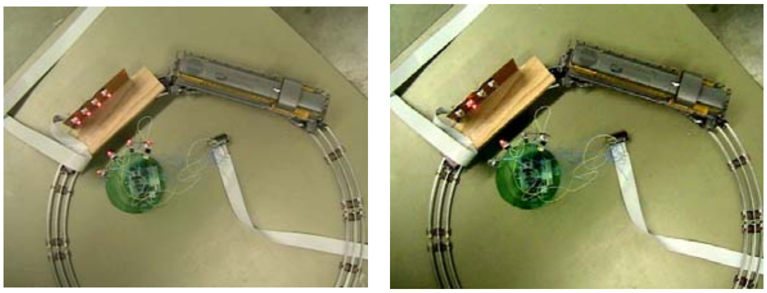


Fig. 1: Schematic of the auto-alignment circuit with 4 channels circuit.



(a) Misaligned (b) Aligned

Fig. 3: Illustration of the mobility experiment using a train.

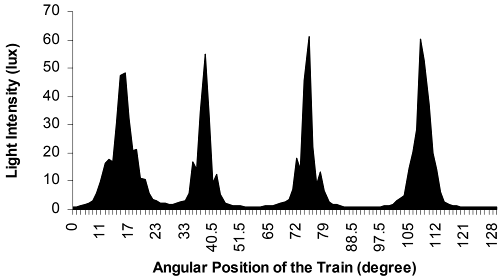


Fig. 2: Intensity at the optical antenna as the train moves along the circle.

fixed FSO communication techniques to remedy small vibrations and swaying of the buildings have been implemented using *mechanical* auto-tracking [17]. However, mobile FSO communication in outdoor distances has not been realized.

In commercial FSO systems, lasers in the 850nm and 1550nm band are preferred due to superior propagation characteristics in this band and higher power budget due to low geometric dispersion. Such equipment would be very costly and demands high-power in the context of multi-element scenario. Moreover, such laser-based equipment would not have the form factor, weight and power characteristics to be mounted on ad-hoc infrastructures. We instead investigate FSO networks using models of LEDs in our design as they are more amenable to dense and spatial packaging, and have longer life than lasers and fewer eye-safety regulations.

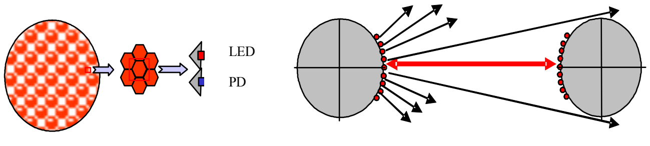
Another motivation for using FSO is that it has potential to provide effective solutions to the last-mile problem in broadband access. Currently, the most effective solution to the last-mile problem is provided by the IEEE 802.16 standard technology [14], which achieves high bandwidth access up to approximately 70Mbps for *stationary* nodes using the band of 10-66 GHz. This achievement provides a good alternative to cabled access networks, such as fiber optical links and digital subscriber lines because of its easier and less expensive deployment. However, this band of operation (i.e. 10-66 GHz) requires LOS just like the LOS limitation inherent in FSO communication medium. Although there is an attempt to realize IEEE 802.16 standard in the 2-11 GHz band [14] which does not need LOS to operate, it is not yet clear whether or not the same high-capacity communication will be possible. Thus, in comparison to the best of RF-based communication, FSO still provides a significant potential to solve the last-mile problem.

III. AUTO-CONFIGURABLE OPTICAL ANTENNA DESIGN

Auto-configurability of our optical antennas is based on two fundamental design components which we detail in the following two subsections. In the third subsection, we will show mobile communication with our optical antenna design.

A. Concept of Tessellated Spherical Optical Antenna

The very geometrical shape of a sphere suggests spatial and angular diversity. We tessellated the surface of a sphere using optical transceivers each of which contains an LED (Light Emitting Diodes) as the transmitter and a photo detector (PD) as the receiver. Since LEDs have relatively high divergence angle and PDs have a comparable angular field of view, the LED-PD pair forms a transceiver cone. This cone covers a significant volume of 3-dimensional space. As shown in Fig. 4(a), a sphere tessellated to an appropriate density can cover entire 360 steradian of the surrounding space. As seen from the Fig. 4(b), when the spheres move relative to each other, an existing LOS between them is lost and a new one is established.



(a) Tessellated Sphere (b) Showing a Line of Sight

Fig. 4. Sphere tessellated with LED+PD transceivers.

B. Auto-alignment Circuit

The basic functionality of the auto-alignment circuit is to monitor the incoming light beams at each transceiver and maintain continuous communication between two non-stationary optical antennas by dynamically latching appropriate transceivers within their LOS. Fig. 1 shows the schematic of the circuit for one optical antenna, with four transceivers.

In the event of misalignment, the circuit first (i) searches for an existing LOS between the two spheres, and then (ii) continues data communication through the new LOS, once a new LOS is established. These two functionalities are implemented in a common hardware for all the transceivers on a single spherical optical antenna. The part of the circuit that monitors an existing LOS is shown as the "LOS Unit", which gives out a logical high output when an LOS is present between the two communicating antennas and a logical low input when the LOS is lost. The logical low output triggers the "LOS searching". During this phase, data transmission is temporarily aborted and search pulses are sent out in all the directions looking for LOS. The second sphere, which now moved to a different location, also drops LOS and hence it too starts to initiate LOS searching. The spheres eventually receive the search pulses upon existence of a new LOS, which causes first a high output from the LOS Unit and then restoration of the data transmission.

For cases when multiple channels are aligned, we used a priority decoder to select a channel via the LOS signals from each transceiver. When no channel is aligned, the system searches for alignment by sending pulses to each channel. As soon as one or more channels get aligned, it starts to send data signal out through the aligned channel. Thus, the logical data channel (or stream) is assigned to the physical channels dynamically depending on whether or not they are aligned.

C. Mobility Analysis

We performed a fun experiment to demonstrate the concept of spatial diversity and LOS auto-alignment in the case when multi-channels are aligned. We built one cylindrical and one planar optical antenna with 4 duplex optical channels on each. Each optical transceiver included an LED with a divergence angle of 24^0 and a PD with field of view of 20^0. We spaced four transceivers on the cylindrical surface with an equal separation angle φ of 32^0 along a circumference normal to the cylinder axis. The planar surface also included four transceivers equally spaced along a line. We then placed the planar surface as part of train's cargo, and moved the train along a circular path of radius 30cm to create relative mobility. As the train moves the transceivers get aligned and misaligned. Fig. 3(a) shows a misalignment instance in which the search pulses are sent out by all transceivers and LEDs are glowing. Fig. 3(b) shows an instance of alignment in which two transceivers are in LOS with each other and data transmission is going through them. This pattern repeats as the train travels along the circular path. Fig. 2 demonstrates the continuous alignment and misalignment phases as the train moves relative to the cylinder. For this setup, we used a light intensity threshold of 33.3lux at PDs to determine LOS. Notice that, LOS periods can be increased by appropriately tuning the light intensity threshold at PDs, the divergence angles of LEDs, the field of view angles of PDs, and by increasing tessellation density. The speed of the circuit should be more than the speed of the relative movement between the spheres so as to maintain a smooth data flow.

IV. SIMULATING MOBILE FSO NETWORKS

The tool that we have decided to use for simulating mobile FSO components is the network simulator NS-2 [13], which is a discrete event simulator targeted at networking research. We selected NS-2 as it is a very comprehensive tool that provides substantial support for simulation of TCP, routing, and multicast protocols over wired and wireless networks.

Unfortunately there are no optical networking features in NS-2. The key issue is that of lacking a realistic propagation model for FSO communication. NS-2 uses propagation models to determine if one antenna can receive signal from another, and if so, determine if that signal is good enough to transmit data over it. This problem is broken into two parts, the first being determining LOS and the second being power calculations. Researching this we have created an FSO propagation model making great use of the work of Kim et al. [9]. Although his work is based more so on laser optics in free space than higher divergence technologies such as LEDs, we have used many components of it in our models because of the conceptual similarity of propagation for lasers and LEDs.

The model that we created has several calculation steps. First we must determine the average power leaving a particular transceiver, which is usually given in the product specification table of any light emitting product. Next we begin calculating loss due to geometric dispersion and loss due to atmospheric attenuation.

When light is emitted from an LED it disperses conically. And at any cross section of this cone the power of the emitted light can be calculated as [9]:

$$\frac{SA_R}{SA_T + \pi/4\,(\theta R)^2} \tag{1}$$

where SA_R is the surface area of the receiver, SA_T is the surface area of the transceiver, θ is the divergence angle, and R is the range in meters.

As the range increases the loss due to geometrical spreading increases, and we simply subtract this loss off from our average power. What remains is loss due to atmospheric effects. The loss of power due to atmospheric attenuation is described by Beer's Law [9]:

$$\tau(R) = \frac{P(R)}{P(0)} = e^{-\sigma R} \tag{2}$$

where $\tau(R)$ is the transmittance at range R, $P(R)$ is the power at R, $P(0)$ is the power at the source, and σ is the

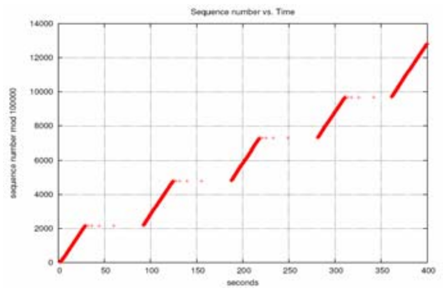


Fig. 5. TCP sequence numbers in Experiment 1.

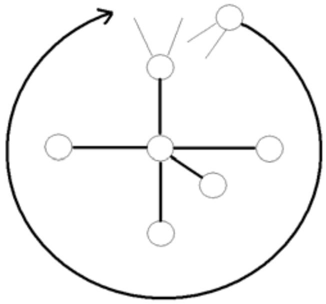
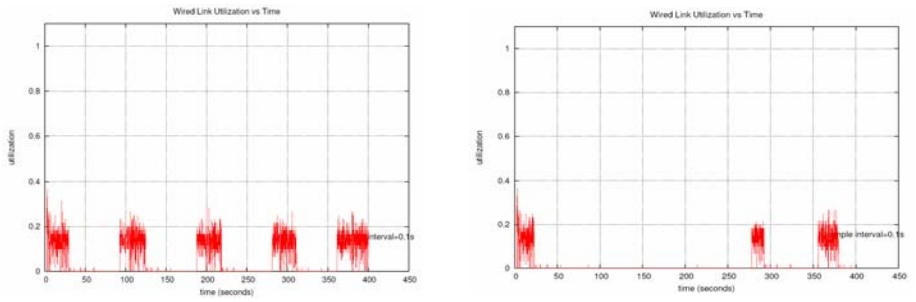
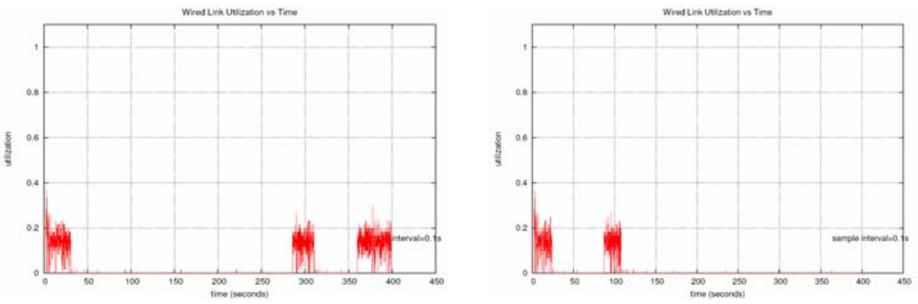


Fig. 6. 2-D Experiment Configuration Sketch (not to scale) – A single FSO node moves around several stationary nodes while transmitting data when alignment is achieved.



(a) Experiment 1.

(b) Experiment 2.



(c) Experiment 3.

(d) Experiment 4.

Fig. 7: Utilization of wired links in the experiments made for the 2-D scenario.

attenuation or total extinction coefficient. The attenuation coefficient is given by:

$$\sigma = \frac{3.91}{V}\left(\frac{\lambda}{550nm}\right)^{-q} \tag{3}$$

where V is visibility in kilometers, λ is the wavelength in nanometers, and q is the size distribution of any scattering particles. Since our experiments are for indoor scenarios the attenuation coefficients are negligible.

The next issue in simulating mobile FSO nodes in NS-2 was to incorporate FSO antennas into NS-2's `mobilenode` class hierarchy. NS-2 mobile nodes already implement omni-directional antennas, thus we have added an additional FSO antenna that can be selected when setting up the simulation. Our FSO antennas have many additional parameters such as directional normals, transmission and receiving angles, among others, to assist the propagation model and LOS calculations. For the experiments we implement functions to place our FSO antennas in our desired configurations. For each FSO antenna that is stationary we place it in a circular or spherical orientation, it is then wired to a central base station which sources or syncs data. Taking each of such singular FSO antennas and placing them into proper orientations, we can simulate any 2-D or 3-D mobile FSO structure.

V. EXPERIMENTAL RESULTS

We simulate a 2-D circular FSO structure to validate our simulation components as well as to present proof-of-concept for possibility of applying spatial reuse and angular diversity for optical wireless access. Making use of our simulation components of FSO in NS-2, we have simulated a 2-D scenario on the XY-plane. In this 2-D configuration, we have a single mobile FSO node which circularly moves around four stationary FSO nodes. The stationary nodes are located in a circular pattern and are connected via wired links to a single central node. As shown in Fig. 5, the combination of the central node and the stationary FSO nodes simulates an FSO device structure with spatial reuse of transceivers and angular diversity for LOS. We characterize these transceivers as photo-detector/LED pairs with the parameters shown in Table I. These single transceivers (nodes) are directional and can only send/receive in a defined direction and angle. The stationary nodes are in a circular configuration with a radius of 10 cm.

TABLE I
TRANSCEIVER CHARACTERISTICS FOR 2-D EXPERIMENTS

Transmitter Power	4 dbm
Transmitter Diameter	3 mm
Transmitter Angle	1.45 Radians
Receiver Sensitivity	-43 dbm
Receiver Diameter	8 mm
Receiver Angle	1.45 Radians

As the mobile node moves around the stationary nodes, an FTP session is alive between the central node and the mobile node. Initially, the experiment starts with the mobile node and one of the out stationary nodes in LOS. Soon after the session is established, the node moves around the stationary nodes at a constant rate of speed. For our experiments, all wired links are 100 Mbps with 2ms delays and Drop Tail queues, while the FSO nodes are configured to only transmit at 20 Mbps[1]. Routing is performed by ad hoc DSDV routing agents and MAC is facilitated by 802.11 that is already present in NS-2.

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[1] Note that this limit of 20Mbps is just our configuration limitation, and is not a physical limitation as modulation speeds can be in the order of GHz in optical bands.

Future work in this area would lead us to design and implementation of an FSO specific MAC protocol, but 802.11 serves us well for our proof-of-concept experiments.

TABLE II
EXPERIMENTAL PARAMETERS FOR 2-D SCENARIO

Experiment	Mobile Node's Velocity	Mobile Node's Path Radius
1	1.5 meters/second	25 meters
2	1.5 meters/second	35 meters
3	2.5 meters/second	25 meters
4	2.5 meters/second	35 meters

We performed four experiments by varying the speed of the mobile node and the distance of the mobile node from the central node, as shown in Table II. As shown in Fig. 7(a)-(d), for each experiment we recorded the utilization of the wired links. Also, we recorded the TCP sequence numbers received by the destination node, as shown in Fig. 5 for Experiment 1. All experiments were run for 400 seconds.

From the plots in Fig. 7(a)-(d) we can see that, using FSO propagation model in the simulation, it is possible to achieve connectivity through mobile FSO communication even with a very small number of transceivers. The experiments were configured in such a manner that LOS is not always present, thus showing that connectivity is reestablished when the nodes are back in LOS. This is demonstrated by the periods of inactivity in the utilization graphs and by the plateaus in the TCP sequence number graphs, which is shown in Fig. 5 for Experiment 1. The TCP sequence numbers for the other experiments also showed similar behavior, where plateaus exist for connectivity periods. Furthermore, increase in the TCP sequence numbers imply that (i) all simulation components from physical layer to transport layer are setup properly, thereby provides validity of our simulation building blocks, and (ii) transport level goodput can be achieved over a highly variant (i.e. frequent LOS changes) FSO environment.

These experiments also demonstrate that, in the cases of high mobility or far distance, the connection may not always be reestablished right away even if LOS is available. This appears to be corresponding to TCP's retransmission attempts. If LOS is passed through in between these retransmissions, connectivity is not reestablished, which is greatly evident in Fig. 7(c)-(d). So, another important conclusion is that transport and network level protocols will need to be optimized for the underlying FSO communication medium, which calls for significant future research on the topic.

VI. SUMMARY

We investigated FSO communication as an alternative to RF-based communication technologies for mobile wireless networks. To enable mobile FSO communications, we proposed and developed a novel optical antenna using (i) spherical surfaces tessellated with optical transceivers to obtain spatial diversity, and (ii) an auto-configurable optoelectronic circuit that makes use of this diversity to enable mobility between communicating antennas. We built a prototype system and demonstrated optical data transmission between mobile nodes. The basic techniques can be extended to configurations containing more than two nodes at longer distances. One key feature of our design is the absence of mechanical parts such as motors or moving mirrors typically used for auto-alignment purpose. This leads to significant savings in power consumption and improved reliability.

We also developed NS-2 simulation components to simulate FSO propagation and mobile FSO nodes. Our initial simulation results show that a mobile FSO network is a practical approach to mobile wireless networks. We observed by simulation that a mobile FSO network is sustainable with varying degrees of distance, though we can not discount the effects of these parameters either. As user demand outgrows the capabilities of traditional RF wireless networks, we foresee FSO as an excellent solution.

ACKNOWLEDGMENT

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