Multi-Element Free-Space-Optical Spherical Structures with Intermittent Connectivity Patterns

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***Abstract*—Due to its high bandwidth spectrum, Free-Space-Optical (FSO) communication has the potential to bridge the capacity gap between backbone fiber links and mobile ad-hoc links, especially in the last-mile. Though FSO can solve the wireless capacity problem, it brings new challenges, like frequent disruption of physical link (intermittent connectivity) and the line of sight (LOS) requirements. In this paper, we study a spherical FSO structure as a basic building block and examine the effects of such FSO structures to upper layers, especially to TCP behavior for stationary and mobile nodes.**

***Index Terms*—Free-space-optics, FSO-MANET, mobile ad-hoc networks, spherical FSO structures**

I. Introduction

The capacity gap between RF wireless and optical fiber (wired) network speeds remains huge because of the limited availability of RF spectrum [1]. Though efforts for an all-optical Internet [2]–[7] will likely provide cost-effective solutions to the last-mile problem within the *wireline* context, high-speed Internet availability for mobile ad-hoc nodes is still mainly driven by the RF spectrum saturations, and spectral efficiency gains through innovative multi-hop techniques such as hierarchical cooperative MIMO [8]. To achieve high-speed wireless point-to-point communications, free-space-optical (FSO) communication has received attention particularly for high-altitudes, e.g. space communications [9] and building-top metro-area communications [10], [11]. Main focus of these efforts has been on reaching *long* (i.e. ∼kms) communication distances with *highly expensive* (e.g., lasers) FSO components using highly sensitive mechanical steering technologies.

Free-space-optical transceivers are cheap (less than \$1 per transceiver package), small ($\sim 1mm^2$), low weight (less than 1gm), 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).

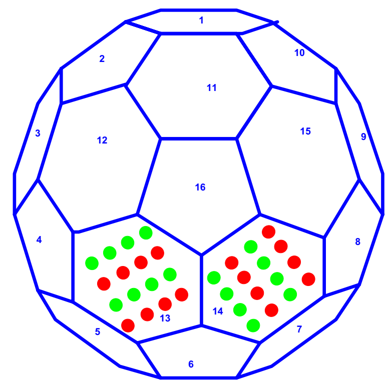

Fig. 1. Optical Antenna: A spherical FSO node formed of hexagonal board in a "soccer-ball-shaped" arrangement. Each hexagonal board has VCSEL lasers and photo-detectors with their associated circuitry mounted in an array.

Recently, we showed that [12]–[14] 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. Such FSO spherical structures (i) achieve *angular diversity* via spherical surface, (ii) achieve *spatial reuse* via directionality of FSO signals, and (iii) are *multi-element* since they covered with multiple transceivers (e.g., LED and photo-detector pair). In this paper, we examine the research problems brought by using such structures in MANETs.

The rest of the paper is organized as follows: We first describe the spherical multi-element FSO structures in Section II. Then in Section III, we cover characteristics of FSO propagation and describe the propagation model we use in our simulations. We present our initial simulation results for FSO-MANETs while comparing those results against the ones from RF-based MANETs in Section IV. Finally, we summarize our work.

II. Multi-element FSO Spherical Structures

Spherical FSO antenna design employs packed deployment of inexpensive transceivers for covering a spherical surface. Figure 1 shows the general concept of spherical surfaces being covered with FSO transceivers, i.e., a pair of optical transmitter (e.g. Light Emitting Diode (LED)) and optical receiver (e.g. Photo-Detector (PD)). To achieve minimum geometric loss due to beam divergence, it is desirable to have the size of

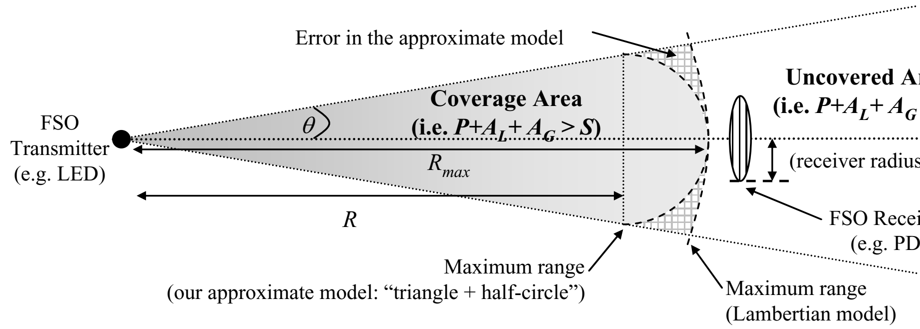

Fig. 2. Maximum communication range of a single LED defines the border of the communication coverage area.

the transmitter as small as possible and receiver as large as possible.

Our design of such FSO structures is based on two principles; (i) spatial reuse and angular diversity via directional transceivers tessellated on the surface of the spherical node and (ii) auto-alignment circuitry that establishes alignment of two transceivers after a misalignment period. Auto-alignment circuitry, contrary to mechanical steering mechanism, delivers quick and auto hand-off of logical flows among different transceivers, while achieving a virtually omni-directional propagation and spatial reuse at the same time. Auto-alignment circuit monitors incoming light intensity at each transceiver. Whenever the light intensity drops under a predefined threshold, the search phase begins to re-establish the alignment. When two nodes are misaligned, a search signal is sent through all misaligned transceivers. Upon receiving a search signal, the circuitry determines the newly established alignment and restores data transmission.

Briefly, the LOS alignment is detected in a two-phased fashion [12]: 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, which causes first a positive LOS availability and then restoration of the data transmission.

We simulated these FSO spherical structures in ns-2 [15]. In our simulation design, we assume that LOS is established automatically by using the technique described above. With careful tuning of various component parameters of the proposed antenna (i.e. divergence angle, density of transceivers) to achieve maximum spatial coverage [14], we observed that even mobile connectivity can be established with acceptable transmission rates under very high speeds. Our research reveals that such nodes bring several new challenges. These include quick and auto-handoff of logical transmission channels (e.g., a file transfer at the transport layer) across physical channels, i.e., FSO transceivers.

III. FSO Propagation Model

To make our simulation results realistic, we revised the ns-2 implementation of a wireless channel. We used well-known FSO propagation models [16] to simulate power attenuation characteristics of an FSO signal. LEDs' light intensity profile (Figure 2) follows the Lambertian law [16], i.e. intensity is directly proportional to the cosine of the angle from which it is viewed. At a distance Z, let the received power on along the beam be . Based on the Lambertian law, at an arbitrary angle α from the vertical axis and at a distance Z, the intensity would be: $P_{\alpha,Z} = P_Z cos(\alpha)$. For edge-emitting LEDs, this is improved by a factor u in the power of cosine, i.e. the intensity is given by: $P_{\alpha,Z} = P_Z cos^u(\alpha)$.

Also, as a generic definition for all FSO transmitters, the beam radius w_Z at the vertical distance Z is defined as the radial distance at which the received power is $\frac{1}{e^2}P_Z$. So, the divergence angle θ is the special value of α, where the ratio $P_{\alpha,Z}/P_Z = 1/e^2$ holds, which means θ can be calculated by $\theta = tan^{-1}(w_Z/Z)$.

FSO propagation is affected by both the atmospheric attenuation A_L and the geometric spread A_G, which practically necessitates the source power to be greater than the power lost. The *geometric attenuation* A_G is a function of transmitter radius γ, the radius of the receiver (on the other receiving FSO node) ς cm, divergence angle of the transmitter θ and the distance between the transmitting node and receiving node R:

$$A_G = 10\log\left(\frac{\varsigma}{\gamma + 200R\theta}\right)^2$$

The *atmospheric attenuation* A_L consists of absorption and scattering 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 [16] as:

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

where σ is the attenuation coefficient consisting of atmospheric absorption and scattering. For the wavelengths used for FSO communication, Mie scattering dominates the other losses, and

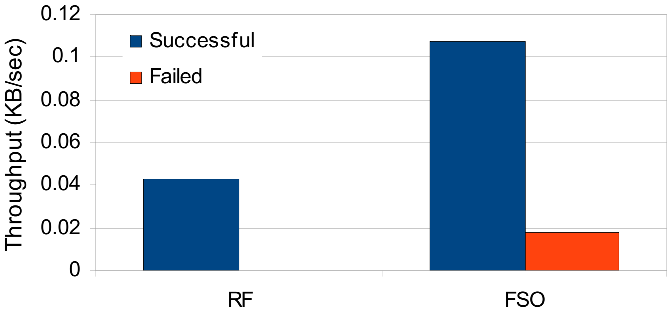

Fig. 3. RF and FSO comparison in a stationary scenario. FSO outperforms RF in stationary scenario but introduces a high error rate.

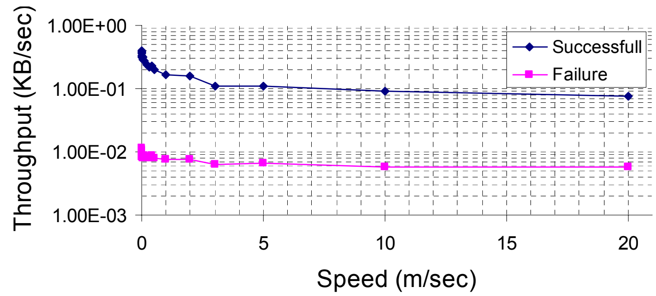

Fig. 4. Mobile FSO simulations with varying speed: As the mobility is increased the overall throughput of the network decreases. Y-axis is in logarithmic scale.

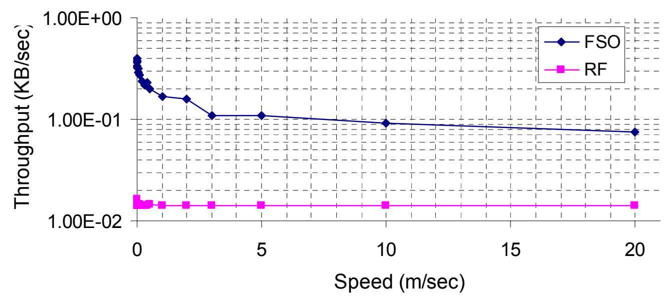

Fig. 5. Mobile RF and FSO comparison: FSO outperforms RF in mobile case proving (even high) mobility can be achieved experiencing better throughout than RF. Y-axis is in logarithmic scale.

therefore is given by [17]:

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

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 visibility:

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

IV. Performance Evaluation and Simulations

To perform the comparative evaluation of RF- and FSO-based MANETs, we conducted several ns-2 simulation experiments. The two basic experiments that we conducted consist of 49 nodes and take place on a 210m$\times$210m area. The nodes are placed 10m away from each other, thereby posing a perfect grid topology. For the mobile simulation scenarios, the nodes move away from their initial points of placement and break the grid topology. We assign transmission power for both RF and FSO cases such that each node can talk with 99% probability (i.e., with BER of 1%) to their immediate neighbors 10m away from it. In other words, a node in the middle of the grid will be able to establish links to its four neighbors located up, down, right, or left.

Traffic model is composed of $49\text{x}48$ TCP flows. FSO nodes in the simulations have 4 transceivers with 2.5cm of photo detector diameter and 0.5cm LED diameter. Medium has the visibility of 6km and the node radius is 5cm. We used the *setdest* utility, that comes with the ns-2 package, to generate mobility scenarios based on random way point mobility model. Note that the node radius is pretty small and the distances among nodes are relatively very large. We intentionally chose these values to investigate a close to worst-case scenario.

Figures 3 and 4 show the per-flow TCP throughput in the stationary and mobile simulations respectively. Stationary simulations of FSO and RF reveal that FSO performs much better than RF despite the conservative decisions in simulations. Considering that specific FSO setup used in this simulation suite accommodated only a small number of transceivers (i.e., 4), stationary results provide a promising starting point.

Mobility poses a great challenge for FSO networks that require clear line of sight. As mentioned previously, intermittent connectivity pattern in mobile FSO causes underlying physical link to disconnect very frequently. This pattern causes TCP performance to degrade dramatically. As in Figure 4, TCP performance decreases as the mobility parameter of the simulation is increased.

Our simulation results in Figure 5 reveal that FSO achieves better throughput than RF in scenarios where nodes are moving with speeds up to $20m/sec$ according to the random way point algorithm. RF transmission powers are calculated using *threshold* utility which also comes with ns-2 package. FSO powers are calculated according to the FSO propagation model explained.

Figure 6 shows results of a simulation scenario in which we kept the transmission power and all other parameters the same, while expanding the modeled area from 70m$\times$70m up to 14km$\times$14km. From the graph, we can conclude that overall throughput of both FSO and RF drop severely since the power is not adjusted accordingly.

Another simulation scenario (Figure 7) adjusts the transmission power of both FSO and RF while expanding the simulation area. The transmission power is adjusted such that each node can establish 1% BER communication links to

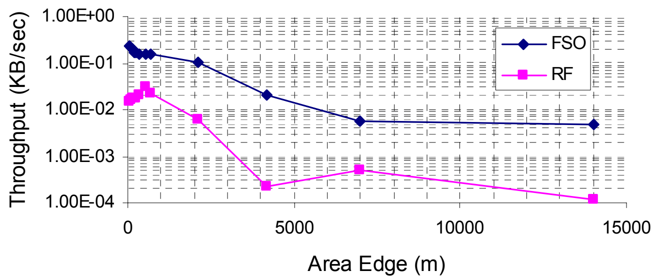

Fig. 6. Throughput drops dramatically for both FSO and RF when the simulation area is expanded but the transmission power is kept the same.

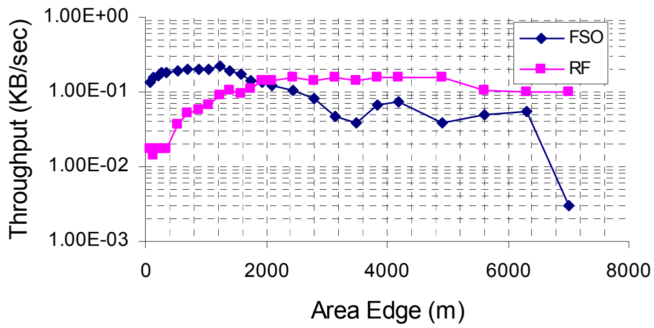

Fig. 7. RF and FSO converge to a common throughput when the transmission power is adjusted accordingly. Later on, RF performs better than FSO for larger areas.

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.

V. Summary

This paper outlines an initial simulation study of FSO-MANETs using spherical structures covered with multiple transceivers. Because of the fundamentally different error behavior of the medium and highly intermittent connectivity pattern caused by the problem of line-of-sight, we need to redesign link layer buffering mechanisms to remedy the intermittent connectivity and provide a smoother link to the upper layers. We observed that TCP congestion control mechanisms get very adversely affected due to this new kind of link error behavior. Overall, upper layers of the networking stack need to be redesigned, since the error behavior of FSO links are fundamentally different from regular RF links.

Future work includes link layer protocol designs due to the fact that a highly intermittent connectivity pattern is presented by the proposed FSO structures when they are mobile. For the mobile cases, network performance suffers from the high intermittent connectivity nature. Employing a link layer that buffers the packets during the period of misalignment, and provides a virtually continuous connection is necessary. Per interface MAC is being used in the FSO simulations which leaves the decision of which interface to use for a given packet to the routing agent. We propose to change this behavior by employing multi-channel MAC and layer-2 buffers, thus being more proactive in mobile cases by determining alignment and misalignment at the MAC level.

Acknowledgment

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