Throughput Characteristics of Free-Space-Optical Mobile Ad Hoc Networks

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ABSTRACT

Wireless networking has conventionally been realized via radio-frequency-based communication technologies. Free-Space-Optical (FSO) communication with an innovative multi-element node design leverages spatially-diverse optical wireless links; making it a viable solution to the well-known diminishing per-node throughput problem in large-scale RF networks. Although it has the advantage of high-speed modulation, maintenance of line-of-sight between two FSO transceivers during a transmission is a crucial problem since FSO transmitters are highly directional. In this paper, we present our simulation efforts to make high-level assessments on throughput characteristics of FSO-MANETs while considering properties of FSO propagation and existence of multiple directional transceivers.

Categories and Subject Descriptors

C.2.1 [**Network Architecture and Design**]: Wireless communication—*Free-space-optical wireless networking*

General Terms

Design, Performance, Theory, Verification

Keywords

Free-space-optics, mobile ad-hoc networks, angular diversity, spatial reuse, directional communication, spherical FSO structures

1. INTRODUCTION

The capacity gap between RF wireless and optical fiber (wired) network speeds remains huge because of the limited availability of RF spectrum [12]. Though efforts for an all-optical Internet [17, 18, 33] 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 [22]. To achieve high-speed wireless point-to-point communications, free-space-optical (FSO) communication has received attention particularly for high-altitudes such as space communications [10] and building-top metro-area communications [1, 3], and interconnects made of expensive and sensitive materials [14, 24]. Main focus of these efforts has been on reaching *long* (i.e., ∼kms) communication distances with *highly expensive* FSO components (e.g., lasers) using highly sensitive mechanical steering technologies to remedy vibration or swaying issues.

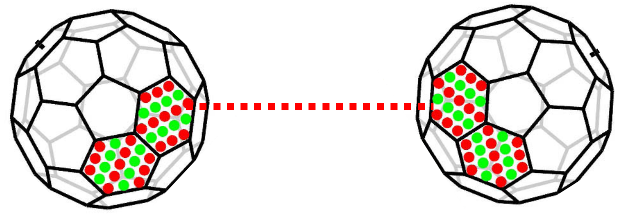


Figure 1: Two "soccer-ball-shaped" optical antennas, accommodating an array of transceivers mounted on each hexagon, are communicating with each other.

An FSO transceiver is a pair of optical transmitter (e.g., Light Emitting Diode (LED)) and optical receiver (e.g., Photo-Detector (PD)). Such optoelectronic transceivers are cheap, small, low weight, 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 and security, 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. FSO communication also suffers from beam spread with distance (tradeoff between per-channel bit-rate and power) and unreliability during bad weather especially when size of particles in the medium are close to the used wavelength (aerosols and fog).

Recent work showed that [4, 7, 8, 19, 26, 34] FSO mobile ad-hoc networks (FSO-MANETs) is possible by means of "optical antennas", i.e., FSO spherical structures like those shown in Figure 1. Such FSO spherical structures (i) achieve *angular diversity* via spherical surface, (ii) achieve *spatial reuse* via directional optical transmitters, and (iii) are *multi-element* since they are covered with multiple transceivers.

FSO communication can be used in indoor or outdoor settings where existing lighting infrastructure can also be leveraged for communication purposes. For example, in a traffic setting where accident information must be delivered to the cars in the same road, FSO can be used to deliver this information using traffic lights as

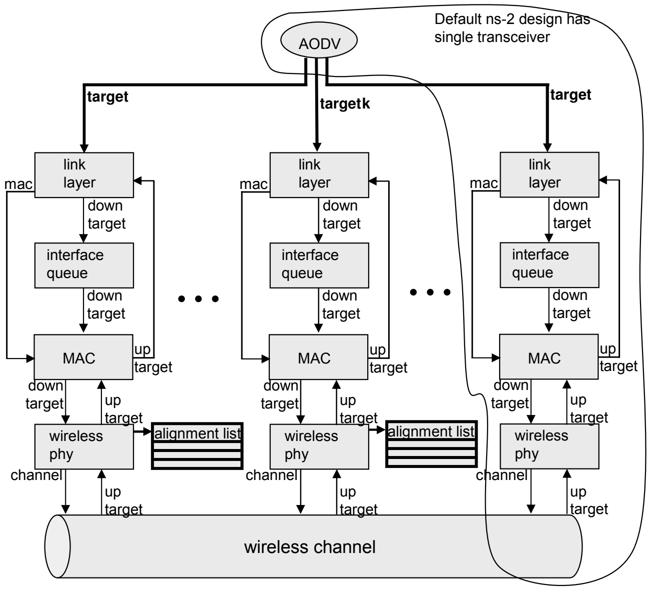


Figure 2: FSO node structure with a separate stack for each optical transceiver.

well as cars' lights in a multi-hop manner. Similarly, traffic lights can be used to serve commercial audio or video content. Furthermore, exit lights inside the buildings can communicate with the hand held devices of disaster victims to direct them to the nearest safe exit.

In this paper, we examine a subset of the research problems brought by using such multi-element FSO structures in MANETs and proposals to remedy such issues. We specifically investigate the issues raised by directionality in combination with mobility, and their implications on TCP and overall network throughput. We present a thorough simulation study that covers all the important system parameters. Our previous work [26] showed that using multi-transceiver FSO nodes to establish a general-purpose communication method is possible via a proof-of-concept prototype made of off-the-shelf optoelectronic components. In this paper, we extend the study to MANET scenarios involving many of such multi-transceiver nodes, and investigate achievable throughput gains in comparison to a pure RF-based MANET. Our contributions include:

- Quantification of negative effects of multi-element FSO structures on end-to-end throughput.
- Modules to realistically simulate FSO nodes in NS-2 with consideration of crucial parameters such as visibility, divergence angle, line-of-sight, alignment, and obstacles.
- A quantitative analysis of overall performance of FSO networks and their comparison to similarly designed RF networks.
- Proposals for solving the intermittent connectivity problem for multi-transceiver FSO nodes.

The rest of the paper is organized as follows: In Sections 2 and 3, we give the literature background information for FSO networks and the theoretical model for optical propagation in free space, respectively. In Section 4, we discuss the details of our contribution to NS-2 to accurately simulate networks of multi-element FSO nodes. In Section 5, we illustrate the observed throughput change

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

Table 1: Table of default parameter values common to each simulation set in our experiments.

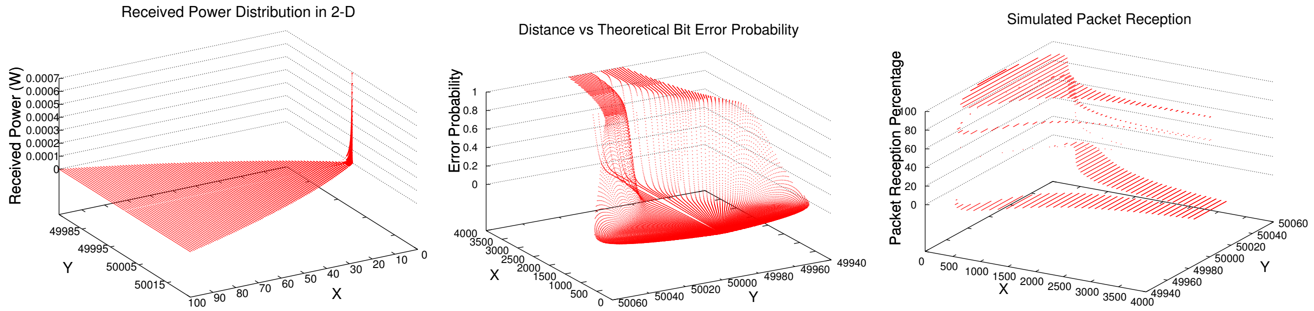
while altering mobility, visibility and divergence angle in the system. We also look at the density of nodes in the network and its implications on throughput as well as other system parameters. Later, we focus on specific use cases of FSO in which there are obstacles: a city environment and a lounge setup and compare the results with RF. We discuss our conclusions and future work in Section 6.

2. BACKGROUND

Majority of the current deployments of FSO communications is targeted at long distance point-to-point applications: terrestrial last-mile, deep space [10] and building-top installations where limited spatial reuse (or redundancy) is achieved through one primary beam and some backup beams. Building-top installations employ high speed modulation of laser, that is generated by expensive and highly sensitive equipments [1, 3] to expand the transmission range and overcome the challenges of propagation medium (especially fog and aerosols). This kind of FSO deployment is typically a mesh network installation in which FSO links establish the backbone of the network, because of their high throughput capacity. Eliminating the need to lay cable, especially in geographically challenging environments is the main motivation of building-top and last-mile point-to-point FSO deployments. Various techniques have been developed for such stationary deployments of FSO to tolerate small vibrations [6], swaying of the buildings and scillantation, using mechanical auto-tracking [5, 9, 20] or beam steering [32], where the main focus was on small vibrations or swaying but node mobility was not even considered possible.

Employment of FSO communication in indoor environments has been done mainly by using diffuse optics [11, 13, 16]. Such proposals have been challenged due to limited power of a single source that is being diffused in all directions. Also quasi-diffuse techniques use multiple transmitters (still with very large angles) to overcome the sensed power problem. Since they rely on the reflected signals in a bounded propagation medium (e.g., in a small room), they have limited range (10s of meters) and are not suitable for outdoor use.

The idea of using multiple elements/transceivers in FSO communication has been used in interconnects [24, 28–30], which communicate over very short distance (e.g., cms) within a computer rack or case. The main issues of such multi-element operation are interference (or cross-talk) between adjacent transceivers due to finite divergence of the light beam, and misalignment due to vibration.



(a) Received power in the field of view of a 1 rad light source.

(b) Probability of error increases as a receiver is moved away from the transmitter.

(c) Percentage of successfully delivered packets versus separation.

Figure 3: Characterization of a free-space optical link.

Multi-element operation has been suggested not only for increasing the capacity of the overall system, but also for achieving robustness due to spatial diversity in the case of misalignment. Our work considers multi-element FSO designs as a general-purpose communication technology working over distances much longer than the interconnects.

Leveraging of multiple directional transceivers in RF-based MANETs was also considered recently. Similar to our electronic steering among FSO transceivers to track line-of-sight alignment, authors of [21] dynamically optimized the best way of selecting a stationary access point and directional RF antenna on a moving vehicle in a seamless manner. In the same vein, several link layer techniques [25, 27] used directional RF antennas to improve wireless multicast throughput. The trade-off between wireless beam directionality and diversity has been an attractive research topic [23], and our work mainly targets establishing building blocks to explore this key trade-off in FSO networking.

3. FSO PROPAGATION MODEL

We used well-known FSO propagation models [32] to simulate power attenuation characteristics of an FSO signal. LED's light intensity profile follows the Lambertian law [32], 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 along the beam be P_Z. 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:

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

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 [32] as:

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

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 therefore is given by [31]:

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

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:

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

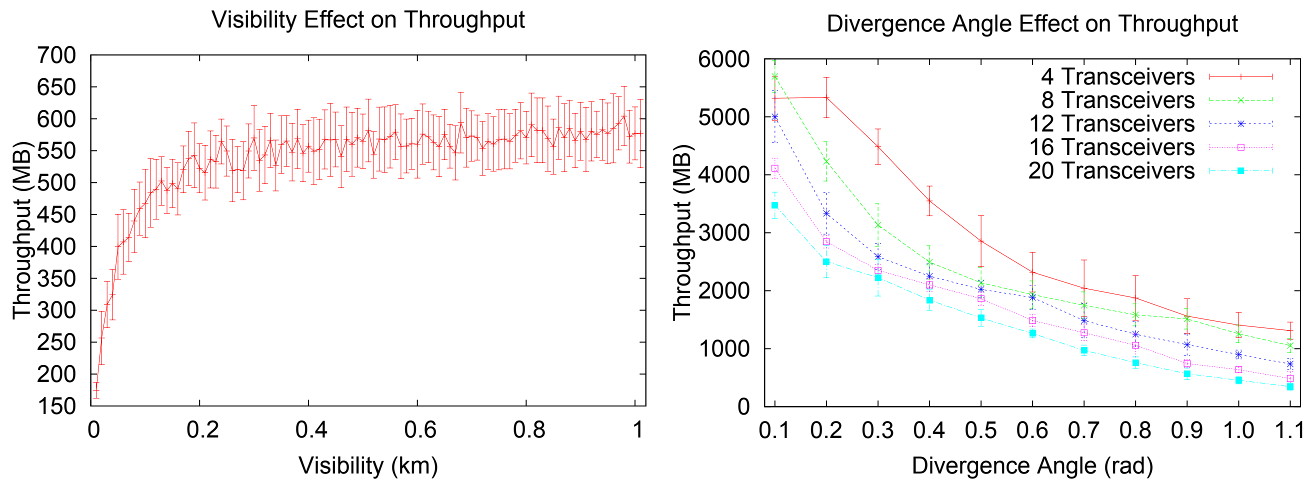
4. MULTI-TRANSCEIVER FSO NODES

To accurately quantify the throughput characteristics of FSO-MANETs, we developed extensions to the well-known network simulator NS-2 [2]. A necessary extension item was to enable multiple transceivers in a wireless mobile node to transmit and receive data simultaneously. For this purpose, we duplicated the stack elements that belong to physical and link layers. This modification essentially required us to change the routing agent and necessary routing table constructs to make it aware of multiple physical interfaces. Moreover, we introduced an alignment list structure for each of these interfaces to keep track of the alignment states of each transceiver. The alignment list of a transceiver contains information revealing the identifiers of currently aligned target transceivers. Physical channel implementation is also modified to make use of the alignment lists to deterministically consider only this list of candidate recipients to further determine if a successful transmission of a packet is achievable. In this section, we discuss our contributions to NS-2 to make assessments on FSO-MANETs' throughput characteristics.

4.1 Wireless Mobile Node Modifications

We used AODV in our simulations as the routing agent. The routing agents available in NS-2 that can be used in mobile wireless nodes assume there is only one interface. We modified this behavior and made AODV capable of handling multiple interfaces. For each interface, there exists a complete set of stack objects from AODV down to physical channel (Figure 2).

This model of dedicating a separate stack for each transceiver enables the wireless mobile node's MAC interfaces to conduct the



(a) Visibility Effect. (b) Divergence Angle Effect.

Figure 4: Aggregate throughput results for different simulation scenarios.

medium access control responsibilities asynchronously from each other. That is, since there are n MAC objects in total for n transceivers, there can be n *simultaneous* flows to different nodes. This is essential to our simulation effort since it enables us to exploit *spatial reuse* of the physical medium in FSO communication. As a future direction, we would like to unify those n stacks into one using a directional MAC which can essentially cope with n simultaneous flows through n transceivers but takes its packets from only one queue object. We expect to see increased responsiveness to mobility since it is aware of the directional nature of the underlying communication channel.

4.2 LOS Re-alignment Mechanism

In a multi-transceiver wireless mobile node setting, a node has to keep track of its aligned transceivers. Instead of more traditional methods like mechanical steering, we use electronic LOS tracking and management, i.e., *electronic steering*. We use a fairly straightforward alignment re-establishment protocol. A transceiver periodically sends out search (SYN) packets to find out if a link can be established. If a neighbor node's transceiver receives such a search packet, it responds accordingly with a SYN_ACK packet. Finally, an ACK packet completes a 3-way handshake which ensures that the alignment is mutual, that is, both transceivers are in line-of-sight with each other.

This periodic re-establishment of alignments has implications on the delivery process of a packet. Routing agent assumes that each interface has multiple wireless physical links to different nodes and it places packets accordingly in the appropriate queue. As soon as MAC discovers an opportunity to send out a packet, it takes a packet from the queue and forwards it to channel object after an RTS/CTS exchange. At this point, channel checks if the next hop is in the alignment list of the sending transceiver (Figure 2). Moreover, if the next hop is in the alignment list, channel checks once more to determine if the two interfaces are still aligned. Note that the role of the alignment list is sufficiently exerted by the first check. Channel implementation is being conservative by conducting the second check, since, although the next hop node is in the alignment list of the sender, it may have gained mobility and lost its line-of-sight.

Finally, our LOS establishment and tracking mechanism conservatively assumes that links are bi-directional. It is possible to extend our LOS re-alignment algorithm such that uni-directional links can be established. Such a uni-directional alignment model would increase the spatial reuse and the effective throughput by leveraging scenarios where forward and reverse transmission channels go over different transceivers and/or multiple hops. For instance, node A can send to node B via its transceiver 1 while node B can respond to node A's transceiver 3 back via node C. Such optimizations are quite possible in stationary or low-mobility settings, and it will require a MAC protocol customized for this directional multi-transceiver environment.

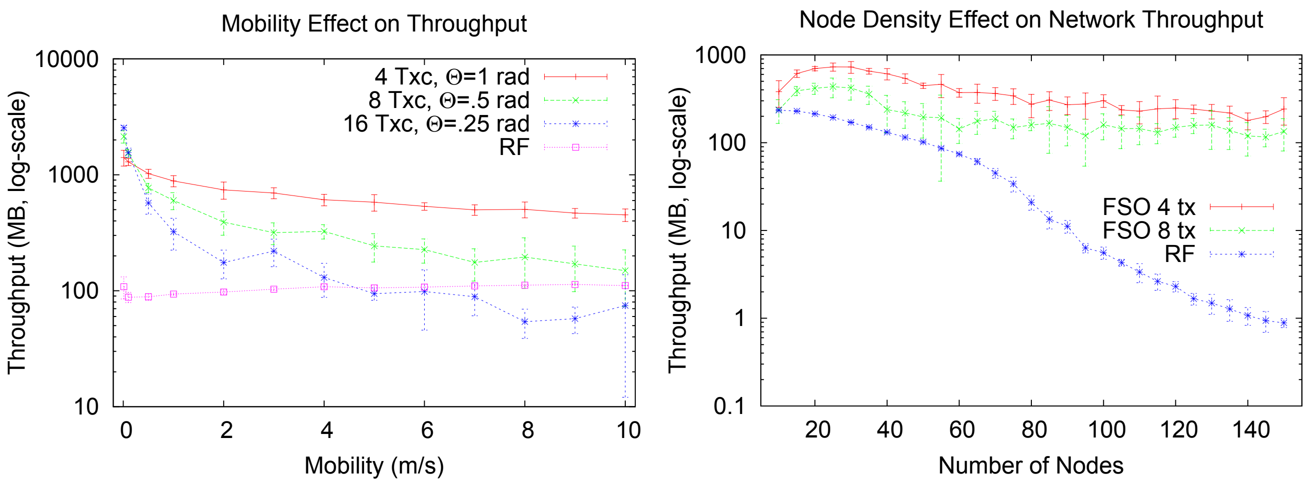
4.3 Characterization of a Single-Hop FSO Link

After introducing necessary mechanisms to simulate multi-element FSO nodes, we validated [8] the single hop FSO link that it conforms to the well-known FSO propagation models [32]. We specifically looked at the power reception and theoretical bit error probability and investigated the conformance of simulated packet error to those two. Figure 3(a) shows the drop in the received power with respect to the separation of transmitter and receiver.

We calculate FSO transmission power for a given range, d meters, such that a receiver that placed exactly on the transmitter's normal experiences a bit error rate of 10^{-6}. Thus, for distances greater than d meters, the receiver experiences increased BER but still continues its communication. This effect can be clearly seen in Figure 3(b) where original source power is calculated for only 0.1 m but the electro-magnetic radiation continues if it does not encounter any obstacle. In Figure 3(b), we observe that the bit error probability increases with respect to distance between transmitter and receiver. Figure 3(b) also shows the curves that power reception is measured as the same and hence, the shape of the FSO beam. One can examine Figures 3(a) and 3(b), and observe that the received power along the normal of the transmitter is much higher and because of that, bit error probability stays low for much longer distances along the transmitter's normal. We found that simulated packet error follows theoretical bit error probability in a coarse manner. As depicted in Figure 3(c), we can clearly identify the limits in the area where a receiver will be able to capture incoming packets with a certain probability of error.

5. PERFORMANCE EVALUATION

We perform extensive simulation experiments to investigate end-to-end throughput performance over a FSO-MANET using multi-element spherical FSO nodes. We compare FSO performance to



(a) Mobility Effect.

(b) Network-wide throughput.

Figure 5: Aggregate throughput results for different simulation scenarios.

RF under the same conditions. Particularly, we aim to answer the following research questions:

- How robust can the multi-element spherical FSO nodes be against *mobility*?
- How important are the effects of node design (e.g., number of transceivers per node) and transceiver characteristics (e.g., divergence angle) on the throughput?
- Can the FSO nodes deliver acceptable throughput in a typical *indoor* environment?
- Can the FSO nodes deliver acceptable throughput in an *outdoor* city environment where several obstacles exist?

5.1 Simulation Environment Setup

Our simulations consist of 49 nodes (each with 8 transceivers) organized as a 7 by 7 grid initially before they start moving. Every node opens FTP file transfer sessions on top of TCP to every other node in the network, which makes 49x48 flows in total. All the nodes are mobile doing 1 meter per second except the lounge simulations in Section 5.7 where nodes as stationary. We used an area of 210x210 meters and visibility of the medium was 6 kilometers. We ran the simulations for 3000 seconds and repeated each simulation for 5 iterations. We show the average throughput plots with 95% confidence intervals.

Table I shows the *default* parameters we feed to our simulation experiments. The FSO node structures are circular in shape, except the lounge scenario in Section 5.7 where the nodes are shaped as a sphere. The transceivers are placed on the nodal shape with a deterministic separation, i.e., the distance among any two neighbor transceivers is the same. The node structure has a radius of 20 cm. The LEDs have 0.5 cm and PDs have 5 cm radius.

5.2 Visibility

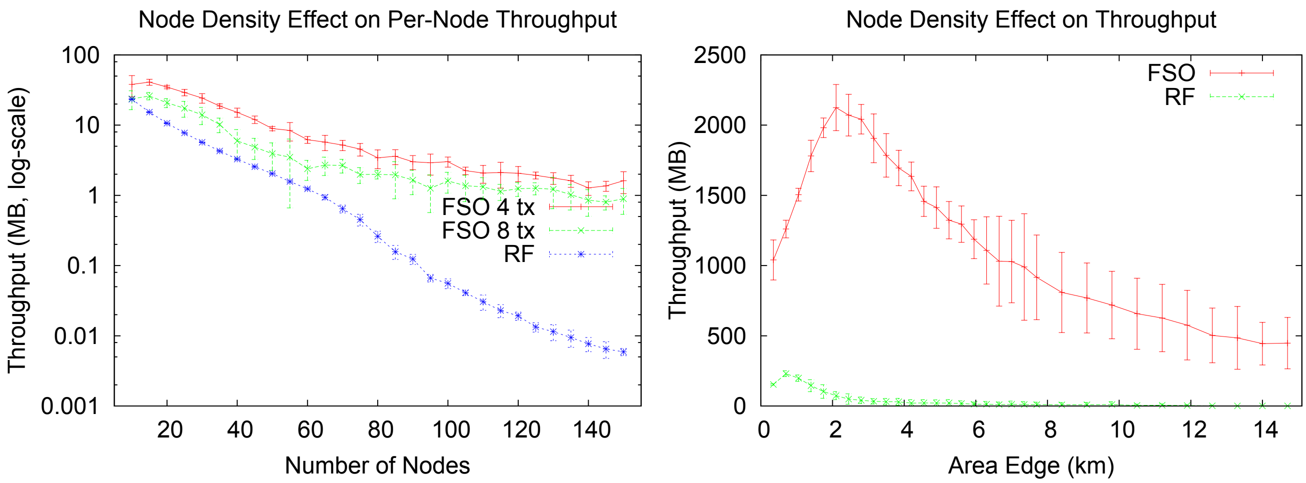
FSO communication has been known for its intolerance to adverse weather. In traditional point-to-point applications of FSO, especially fog has been considered as a serious threat to the reliability of the communication. To quantify how aerosols affect the overall network throughput, we simulated our network scenarios under different visibility conditions. We varied the visibility in the medium from 2 m to 0.2 km. We depict our findings in Figure 4(a) which shows the clear trend of increasing throughput as the visibility conditions become better.

5.3 Divergence Angle

We investigated how divergence angle of transceivers affects the network throughput as well. We used different number of transceivers with varying divergence angles. Number of transceivers change from 4 up to 20 and we increase the divergence angle from 0.1 radian to 1.1 radians. Only different parameter in this scenario from the default setup given in Table 1 is that the mobility of the nodes is 0.01 m/s. One must note that, as we increase the divergence ange of transceivers, coverage area of a node starts to resemble to RF. If the divergence angle is further increased, adjacent beams on a node start to overlap and cause crosstalk and interference. This is why we see a decrease in the overall network throughput in Figure 4(b).

5.4 Mobility

A rather intriguing question is how FSO-MANETs would perform in a mobile setting. We investigate the extent of packet drops caused by mobility and compare FSO-MANETs with similarly designed RF-based networks. To answer this question, we simulated a network of FSO nodes with 4 transceivers, each with 1 radian of divergence angle and other networks of FSO nodes with 8 and 16 transceivers with further decreasing divergence angles. Figure 5(a) shows the results of these experiments. The first observation is that while RF stays almost the same with respect to mobility, FSO throughput decreases dramatically due to the directional nature of the transceivers. Secondly, at low mobility rates, node designs with more transceivers achieve better throughput due to greater spatial reuse. Moreover, node designs with more transceivers and narrower angles tend to get affected more seriously from mobility. We conclude that 4-transceiver design performs the best at high mobility rates since it is the closest one to RF in terms of coverage and wide field of view. From the given results, we conclude that networks of multi-transciever directional FSO nodes exhibit the pattern of *intermittent connectivity*. This event of frequent alignment/misalignment of the communicating transceivers affects TCP seriously. A solution to this problem is to introduce buffers to reduce packet drops in the event of a misalignment as a future direction. Such buffering techniques can be cross-layer in that they should be able to mitigate the loss of layer 2 frames by storing them in layer 2 and/or layer 3 buffer(s) that are either shared by all the transceivers of the node or each one dedicated to different layer 3 flows.



(a) Per-node throughput.

(b) Enlarging Simulation Area.

Figure 6: Aggregate throughput results for different simulation scenarios.

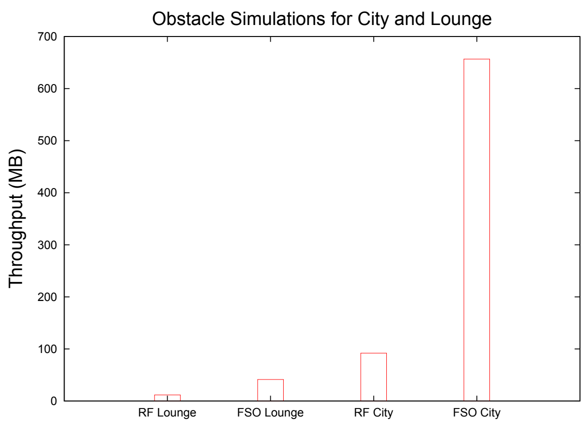


Figure 7: Throughput comparisons for in-door and out-door deployment of RF and FSO.

5.5 Node Density

One of the main motivations behind our work is the reduction in per-node throughput of RF-based MANETs when the network experiences a large increase in the number of actively communicating nodes. RF per-node throughput scales with $\sqrt{n}$ as number of nodes (n) grows [15] since RF spectrum becomes saturated and interference dominates the throughput behavior because of the omnidirectional RF propagation. Hence, we conducted node density experiments in which we increase the number of nodes from 10 to 150 in a confined area of 50x50 meters.

First, we increase the number of nodes in the confined area while keeping area size and the other parameters (e.g., transmission range is 8 m (refer to the discussion in Section 4.3 for power degradation behavior)) the same. Figures 5(b) and 6(a) show the overall network throughput and per-node throughput. We conclude that the drop in RF throughput is much more significant than the drop in FSO throughput in both scenarios, again, because of spatial reuse and decreased interference.

Second, we increase the area size and keep the number of nodes and all the other parameters (e.g., transmission range is 30 m) the same. Figure 6(b) shows the network throughput as one edge of the area is increasing. The network throughput first increases as the node density is decreasing. This shows that the initial node density is too high for the 30 m transmission range and there is a significant interference. Later, as the node density gets even smaller, the network throughput starts to decrease as 30 m becomes insufficient to cover the average node separation.

5.6 Re-alignment Timer

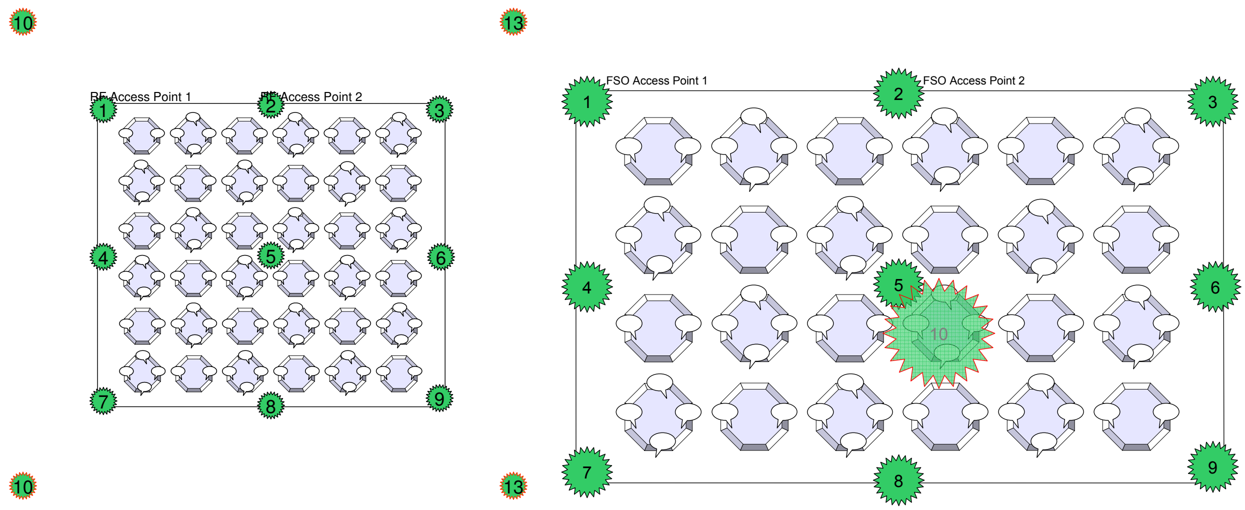
We conducted another set of simulations to find out the effect of re-alignment timer on throughput and failure. We repeated the experiments for 20 iterations with different random seeds and we depicted 95% confidence intervals. In Figure 9, we show how overall network throughput and failure are affected with this phenomenon. Our conclusion is that especially the failures are not dramatically affected with larger timer intervals which is an important finding to reduce the re-alignment overhead.

5.7 Obstacle Scenarios in Lounge and City Environments

We extended our simulation effort to find out how FSO behaves in possible applications in indoor and outdoor environments. For indoor, we considered a lounge setting where there is a dense presence of nodes on top of tables that are 10 m apart from each other. We placed either 2 or 4 spherical nodes on 16 tables which makes 48 nodes each with 18 transceivers. We placed access point FSO nodes with 26 transceivers at arbitrary locations shown in Figure 8(b) including one in a second floor where all the FTP traffic is to and from this node through 9 access points. Similarly, Figure 8(a) shows upper left quarter of the network establishing FTP sessions to and from node 10 through access point 1 The remaining quarters of the network have similar FTP sessions with their corresponding remote nodes where traffic needs to be relayed by an access point node. We observe a significant difference in throughput as shown in Figure 7 in lounge settings due to difference in propagation nature of RF and FSO.

For outdoor, we put 25 (in a 5 by 5 setting) buildings with 10 meters of separation from each other. Between each building, there are 2 people and 1 car. Our re-alignment algorithm takes the obstacles into account so that if a building is blocking two communicating devices, they have to find other intermediate nodes that will carry their traffic. We also modified the default NS-2 random way-point mobility generator to acknowledge existing obstacles. We did not penalize RF transmissions going

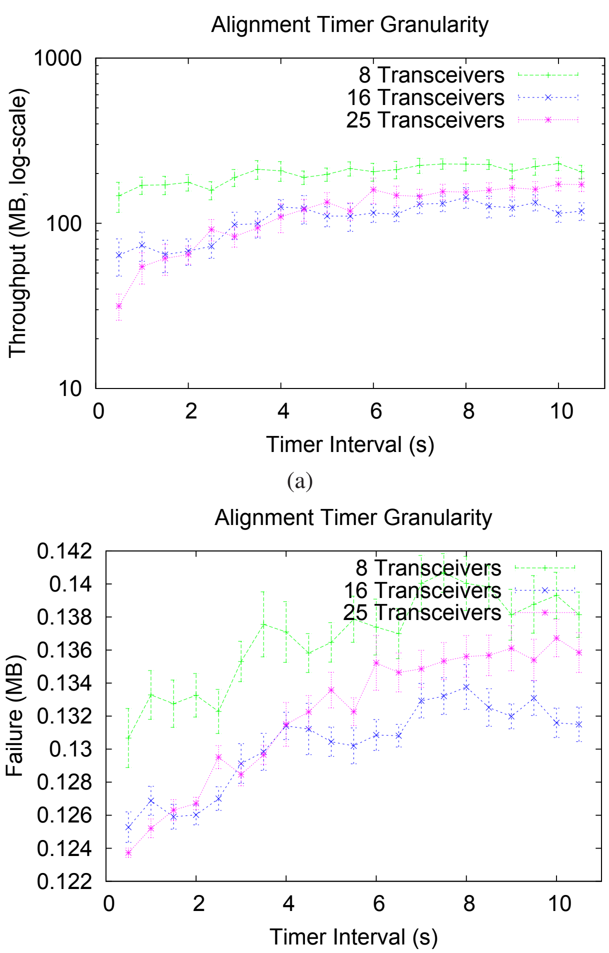
through those obstacles since RF signal can get through obstacles although the signal strength drops in reality. Observe that FSO's



(a) A dense lounge setting with multiple RF wireless devices to demonstrate the substantially decreasing per node throughput problem in RF.

(b) A two story lounge with FSO nodes communicating with another backend node in the second floor.

Figure 8: Placement of FSO and RF nodes in a lounge environment.



(a)

(b)

Figure 9: Alignment timer has a slight effect on throughput, however it does not increase the failures dramatically.

spatial reuse makes a significant difference compared to RF simulation result even though this is an out door scenario (Figure 7). Note that we observe such results since obstacles are blocking the communication only temporarily because of mobility of the nodes.

6. SUMMARY

In this paper, we presented our contribution to NS-2 network simulator, mainly on FSO propagation model, multi-transceiver directional FSO structures, and obstacle-avoiding mobility generation. We assessed the effects of multiple system parameters on the overall network throughput. FSO-MANETs are fundamentally different than RF-based MANETs because of the highly-directional FSO communication in combination with mobility. We conclude that our simulations of FSO networks deployed in lounge and downtown city environments show clear advantage over RF deployments. We plan to introduce a directional MAC implementation and cross-layer buffering schemes to remedy the disruptions caused by intermittent connectivity.

7. ACKNOWLEDGMENTS

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