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Capacity scaling in 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 challenge 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. We identify the intermittent connectivity problem that is caused by the relative mobility of nodes with multiple directional transceivers. We propose two cross-layer buffering schemes to remedy this problem and present their performance results. We conclude that sophisticated buffering mechanisms are required to properly buffer a packet during the misalignment period of two communicating nodes to avoid negative effects of this intermittency on the transport layer.

1. Introduction

The capacity gap[1] between RF wireless and optical fiber (wired) network speeds remains huge because of the limited availability of the RF spectrum [1]. Though efforts for an all-optical Internet [2–4] 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 [5]. 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 [6] and building-top metro-area communications [7,8]. Main focus of these efforts has been on reaching *long* (i.e., ~km) communication distances with *highly expensive* FSO components (e.g., lasers) using highly sensitive mechanical steering technologies to remedy vibration or swaying issues. In parallel to these, another common deployment scenario is interconnects made of expensive and sensitive materials. Similarly, they deal with misalignment issues caused by vibration [9,10].

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 mW 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

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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 [11–17] showed that FSO mobile ad hoc networks (FSO-MANETs) are possible by means of ''optical antennas'', i.e., FSO spherical structures like those shown in Fig. 1. This figure exhibits a sample wireless optical antenna design with hexagonal faces. Each face contains multiple FSO transceivers and each face can be tailored to maintain connection with a neighbor. This hexagonal antenna design introduces the ''group of transceivers'' concept on each face in comparison to uniform spherical design. A group of transceivers can transmit exactly the same signal to increase coverage in expense of some reduced spatial reuse and provide benefits in managing per-flow buffers. 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 and 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 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 as well as to localize them for aftermath rescue [18].

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 [16] 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 and their implications on overall network throughput.

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 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. 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. In Section 6, we propose two buffering mechanisms and provide throughput results to assess their effectiveness. We discuss our conclusions and future work in Section 7.

2. Background

Majority of the current deployments of FSO communications is targeted at long distance point-to-point applications: terrestrial last-mile, deep space [6] and building-top installations, where redundancy or limited spatial reuse 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 equipment [7,8] 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

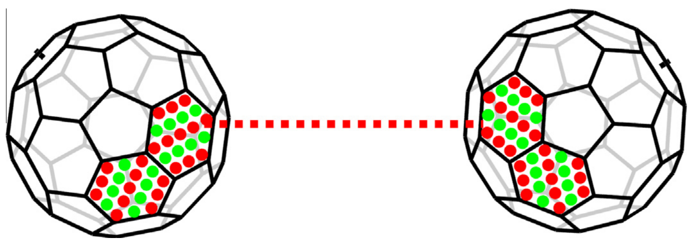

Fig. 1. Two ''soccer-ball-shaped'' optical antennas, accommodating an array of transceivers mounted on each hexagon, are communicating with each other.