

HYBRID FREE-SPACE OPTICS/RADIO FREQUENCY (FSO/RF) NETWORKS FOR MOBILE ROBOT TEAMS

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Abstract In this paper, we introduce a *hybrid free-space optics/radio frequency (FSO/RF)* networking paradigm for mobile robot teams. We believe that such a model will emerge as a consequence of inherent limitations of RF based approaches. FSO technology has the potential to provide tremendous increases in per-node throughput for a mobile ad-hoc network (MANET). To motivate this paradigm, we first provide a brief background on FSO and discuss potential applications where its capabilities could be well leveraged. We then provide initial experimental results from autonomous deployments of a hybrid FSO/RF MANET with real-time video data routed across both optical and RF links.

Keywords: Free-space optics, FSO, MANET

1. Introduction

Over the past decade, mobile robotics research has yielded significant improvements in sensing and control algorithms, enabling levels of autonomy and robustness never before realized (Fox et al., 2000, Dissanayake et al., 2001). These advances were driven in part by the maturation of the underlying technologies: the unimpeded progression of Moore's law, improvements in sensor and actuator technology, and the advent of wireless network communication.

Additional improvements in embedded devices and micro MEMS technology have enabled a second related technology: *wireless sensor networks* (WSN). In a WSN, each sensor node is capable of sensing its envi-

ronment, and collecting/processing data (Nemeroff et al., 2001). Ideally, the WSN is fully connected. Each node has a minimum connectivity degree of three or four, allowing for direct positions estimates. Node connectivity is associative, and bandwidth constraints are insignificant compared to available computational resources. When such idealisms fail to hold, the WSN is congested, disconnected, and incapable of localizing itself in the environment.

The ability to alleviate many weaknesses in static WSNs by introducing mobility has led to the fusion of mobile robotics and WSN technologies, and the formation of *Mobile Ad-hoc Networks* (MANETs). Mobile WSN can achieve otherwise unobtainable levels of robustness and performance (Grossglauer and Tse, 2001). However, MANETs are still bound by the provable limits in per-node throughput for radio frequency (RF) based communications (Gupta and Kumar, 2000). We predict that these limitations will lead to the emergence of *hybrid free-space optics/radio frequency (FSO/RF) MANETs*. While both technologies possess significant limitations, FSO and RF are complementary and have the potential to mitigate each other’s weaknesses.

2. Background and Related Work

2.1 Free Space Optics (FSO): A Brief Overview

FSO is a commercial technology used primarily in static configurations for high bandwidth, wireless communication links (Willebrand and Ghuman, 2002). Degradations in FSO link performance from extreme atmospheric conditions (*e.g.*, heavy fog, smoke, *etc.*) lead to the development of hybrid FSO/RF networks. This was motivated by the need to preserve carrier class link availability (99.999%). In this paradigm, the RF link serves as a low-bandwidth backup to the primary optical link

In FSO, an optical transceiver is placed on each side of a transmission path to establish the network link. The transmitter is typically an infrared (IR) laser or LED which emits a modulated IR signal. This is captured by the receiver at the remote link side. FSO links can be full duplex, meaning that they can transmit and receive data simultaneously.

Several transmitter/receiver link configurations are possible: directed, diffuse, and hybrid (see Figure 1. The former offer the greatest link ranges, and are used for “last mile” commercial network links (Barry, 1994). Diffuse models are often used in “secure” wireless LANs, as unlike their RF counterparts communications can be readily be constrained to a single room. However, diffusing the transmitted signal significantly reduces transmission ranges (to tens of meters).

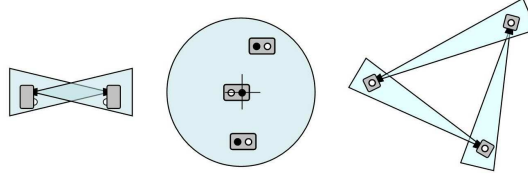


Figure 1. FSO link geometries: directed transmitter/receiver pair (left), diffuse transmitter/receivers (center), and hybrid directed transmitter with diffuse receiver (right).

2.2 Motivation

FSO offers several advantages over RF based technologies. The most significant of these is extremely high throughput across long link distances. Widespread RF technologies (*e.g.*, 802.11x) are limited to link throughputs on the order of 10s of Mbps. Even much anticipated ultra wideband (UWB) technology - with theoretical throughput of 100s Mbps - drops to levels lower than 802.11a at modest ranges ($r \geq 15m$) (Wilson, 2002). In contrast, FSO offers throughputs of several Gbps in currently fielded systems with link distances of a kilometer or more. Fig. 2 highlights the range vs. throughput characteristics of these three mediums. It should be noted that the achievable FSO link distance will be a function of atmospheric conditions. Those reported here are based upon a signal attenuation of 17 dB/km. This corresponds to extremely heavy rainfall (10 cm/hour) or light fog conditions.

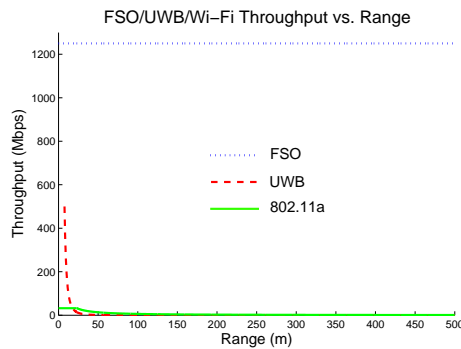


Figure 2. Throughput vs. range for FSO, UWB, and 802.11a technologies. Commercially available FSO transceivers can maintain gigabit+ throughput at distances of 1 km or greater. (Sources: Intel R&D and Canon Canonbeam DT-130).

However, in the realm of mobile networking it has lost in the mainstream computing market to RF technology. This can be attributed to one reason: the requirement for optical links to maintain line-of-sight (LOS). As such, FSO cannot replace RF wireless communications. Instead, the two technologies will serve in complementary modes in a hybrid FSO/RF network. For example, a MANET so equipped could prove invaluable for disaster relief - when some natural or man-made event (*e.g.*, an earthquake) destroys critical infrastructure. In such an application, a team of robots could automatically deploy and provide carrier grade patches to a Metropolitan Area Network (MAN). This could even be accomplished under conditions unsafe for human operators.

Other potential advantages of FSO enabled MANETs include improved node localization. An FSO link constrains the positions of link ends through relative *bearings*. These provide significantly stronger constraints on node positions than traditional range measurements alone (Chintalapudi et al., 2004). FSO also offers low per-bit transmission cost. The directed nature makes it inherently secure, the transmission provides no RF signature, and is also immune to jamming and electromagnetic interference (Barry, 1994).

3. Initial Experimental Results with a FSO/RF MANET

To demonstrate the feasibility of approach, a series of experiments was conducted using “Gollum” and “Balrog” - our in-house mobile robot research platforms (Fig. 3). Each was equipped with a *LaserWire* 100 Mbps optical head, alongside a traditional 802.11 based transceiver.

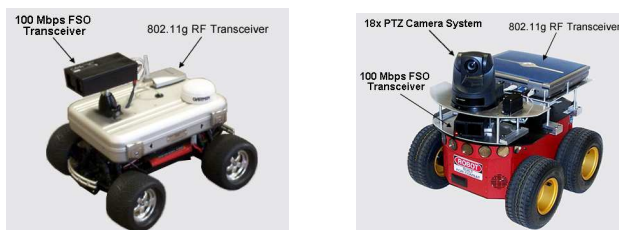


Figure 3. Mobile research platforms equipped with 100 Mbps FSO and 802.11g RF transceivers. “Balrog” (right) also employs an 18x pan-tilt-zoom (PTZ) system for locating link partners at ranges up to 100 meters.

In our preliminary experiments, the objective was to deploy and instantiate a FSO/RF network. The operational scenario is illustrated in Fig. 4, the premise of which is a remote surveillance task. In the initial

configuration, the two mobile platforms were co-located at the far west (left) side of Packard Laboratory. Upon orders from the Command Center (CC), Balrog autonomously deployed to the far east (right) side of the building, traversing a distance of approximately 45 meters. Its task was to transmit local video data from an area of interest (the surveillance zone) back to the CC. The subsequent separation distances between the nodes was such that: 1) No RF link existed between Balrog and the CC, 2) The RF link between Gollum and Balrog provided insufficient throughput for the video stream. These facts necessitated the establishment of an optical link between the two mobile nodes. Thus, in addition to acting as a physical link between the RF and FSO networks, Gollum also had to be capable of forwarding packets between the networks over the correct network interface. This is a routing domain problem that was rectified by configuring Gollum with a packet forwarding (routing) table. A total of 10 deployments were conducted. In each, the robots

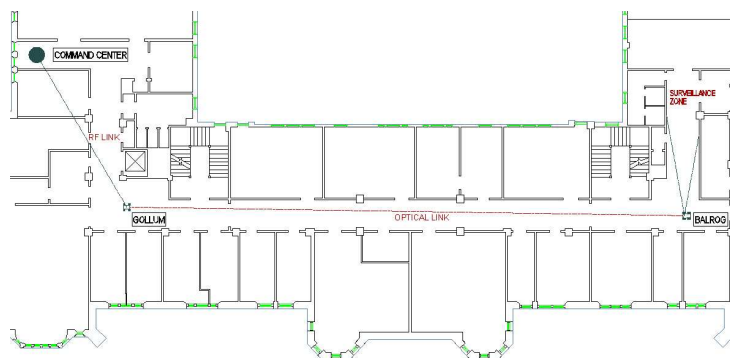


Figure 4. Deployment of a FSO/RF MANET. On orders from the Command Center (CC) (upper left), Balrog deploys to west (right) side of Packard Lab. After establishing the FSO link with Gollum, surveillance video is routed back to the CC over both FSO and RF links.

were successful in deploying and instantiating the hybrid network, and routing surveillance video back to the command center. A sample trial is illustrated in Figure 5. More detailed project information can be obtained at <http://www.cse.lehigh.edu/jcd6/fso/>.

4. Conclusions and Future Work

In this paper, we introduced a hybrid FSO/RF network paradigm for mobile robot teams. Our primary motivation is the tremendous throughput provided by FSO over long link distances. However, the technology



Figure 5. Local surveillance video captured by Balrog (left) and the remote real-time video as viewed at the Command Center

also offers the potential for improved localization performance, low power consumption, and secure/robust transmissions.

To demonstrate the feasibility of this model, preliminary experiments were conducted whereby a FSO/RF MANET was deployed and FSO/RF links established dynamically. Our future work includes the development of a hierarchical vision/FSO based link acquisition system (LAS), and adaptive beam divergence to support mobile operations

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