Synergies of Radio Frequency and Free Space Optics Communication: New Hybrid Solutions for Next Generation Wireless Mesh Networks

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Abstract

In this article, we describe the limitations of radio frequency (RF) and Free Space Optics (FSO) technologies, and show that a hybrid approach that uses both communication media in a suitably coordinated manner is capable of addressing the shortcomings of each. The nature of the required coordination between RF and FSO communication technologies, and the merits derived thereof, are the subject of our research. We report on an initial hardware implementation of a prototype Hybrid RF/FSO node. The properties of the node are used to inform the development of an Integer Linear Programming (ILP) model for this coordination process in RF/FSO networks. We show that by making suitable choices of beam-widths and power levels, the proposed model can be used to design robust hybrid RF/FSO communication infrastructures that minimize power consumption, while satisfying specified joint throughput and end-to-end delay requirements.

Keywords: Hybrid RF/FSO, Wireless Optical, RF, FSO, Topology Control, QoS, Linear Programming.

1. INTRODUCTION

Over the past years, the fields of computer and telecommunication networks have experienced tremendous growth, as many new communication technologies have been developed to help address scalability challenges, arising from requirements in the face of widespread adoption. These requirements include: higher bandwidth, security and privacy guarantees, low end to end delay and responsiveness, high network connectivity and coverage, etc.

In the history of the intellectual development of ideas, there is frequent academic bias towards “pure solutions”—in this case, communication systems that use just one core communication technology. Unfortunately, no single communication technology has been found, to date, which can satisfy all these requirements. For instance, in ad-hoc networks, researchers recently started proposing hybrid models to address the scalability problem in mobile ad hoc networks. These solutions use a sparse network of fixed, wired base stations within an ad hoc network to improve the network properties. In such hybrid networks, nodes can communicate either in a multi-hop fashion using both wireless and wired links. Figure 1 demonstrates an example of such a hybrid ad hoc network. Certainly, a model in mixed nodes (some fixed and some mobile) and mixed edges (some wireless and some wired), is less aesthetically appealing from the vantage point of mathematical uniformity. However, issues of aesthetics aside, the hybrid model has been shown to successfully trade off homogeneity for better performance [2, 4]. Most (but not all) nodes are mobile, and in exchange, nodes sometimes (but not always) have access to an orthogonal communication medium, which they can use to improve network properties. Employing two or more technologies simultaneously, and carefully coordinating their use, in effect leverages the advantages of each while circumventing their weaknesses.

The main shortcoming of the aforementioned hybrid wireless/wired networks is that they have high deployment costs [6]. In establishing telecommunications infrastructures in hostile environments (e.g. disaster recovery and battlefield settings), establishing a wired network is not feasible because of financial costs, setup time, and infrastructure vulnerability. Simply put, a fiber can be cut anywhere along its length, rendering the link inoperative. Since the endpoints of the fiber are static, so is the fiber—and thus the wired communication layer of the network is much more vulnerable to physical attack. How might such vulnerabilities be addressed? First, one might seek to make the links impossible to cut; the only way to break a link is to attack the endpoint node. And second, one might make it easier to move the link endpoint. This is effectively what is achieved by Free Space Optics (FSO) technology.

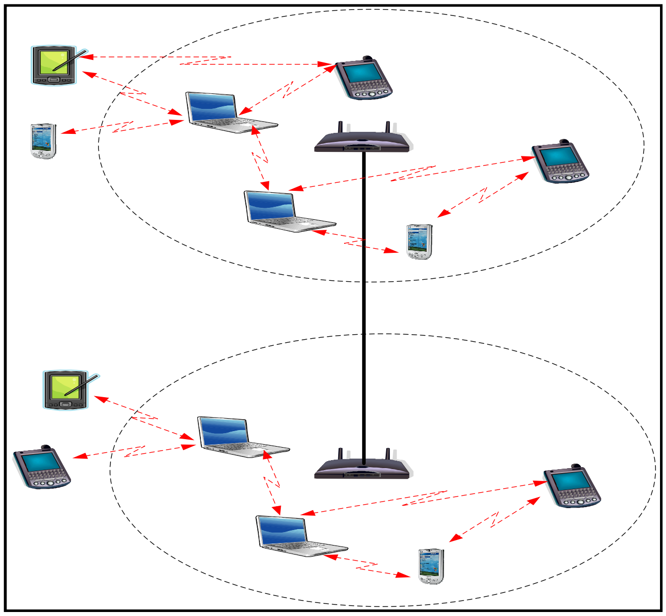

FIGURE 1: Hybrid solution in ad hoc networks.

Historically, FSO was proposed and developed for wireless communications to address QoS, interference, and security limitations of RF. FSO (like wired networks) has the potential for much higher reliable link data rates compared to present RF technology. In addition, because FSO uses directed optical transmissions in which channel beam-width is adjustable, inter-FSO communication interference can be controlled. Finally, the ability to use narrow beam-widths sidesteps the reliance on radial broadcasting in RF; this provides FSO with an advantage over RF in terms of security against eavesdropping [8].

Here consider the coordinated use of Free Space Optics (FSO) and Radio Frequency (RF) communications. At present, most wireless networks are deployed strictly in the RF domain, since RF channels provide natural support for radial broadcast operations. The downside of RF channels is that they introduce many limiting externalities that make providing scalable quality of service (QoS) support difficult, if not intractable [10]. These well-known technical challenges include bandwidth scarcity, high interference, and vulnerabilities to eavesdropping—all of which can be mitigated through the carefully coordinated incorporation of FSO communications. The benefits of FSO do not come without a price, however. Most notable of these drawbacks is the need to maintain line of sight (LOS) between the transmitter and the receiver during the course of communication. In addition, FSO link availability can be degraded by adverse weather conditions like fog, rain, snow, and haze. A hybrid approach that uses both RF and FSO communication must be designed with the strengths and weaknesses of each of the two channel types in mind. One channel type can serve as the “backup” channel and facilitate control of the other type [12].

We believe that the hybrid RF/FSO approach is especially well suited to three application areas: (i) battlefield environments, (ii) intelligent transportation systems (ITS), and (iii) telemetry and telesurgery. In battlefield environments, the hybrid system enables Free Space Optical (FSO) communications bandwidth without giving up RF reliability and “adverse-weather” performance [40]. The RF/FSO technology has many applications in next generation military networks [1] such as:

- Ultra high capacity cross-links between satellites and potentially space-to-air or space-to-ground platforms.
- Airborne networks.
- Air-to-ground links to increase the high-rate RF links currently used for communication.

ITS can benefit from FR/FSO channels in providing a queuing system with alternating service rates [41]. ITS objectives include the development of effective roadside-equipment (RSE) to roadside equipment communication. Unfortunately, the broadcast nature and the low data rates of RF channels make the technology unsuitable for dense deployments. In contrast, the directionality and high data rates of FSO make them an attractive alternative. Telemetry and telesurgery seek to provide of emergency medical care to people in remote areas and/or harsh environments, such as war zones, Polar Regions, or space stations—even if a doctor is not locally available. In this kind of applicatiocn, the surgeons operate using robotic arms, based on a visual feedback from miniature video cameras at the patient location. Receiving such video streams requires reliable and high data rate connections, which are better achieved using a hybrid RF/ FSO [42].

The remainder of this paper is organized as follows: In Section 2, we describe the challenges faced in FSO and RF technologies when considered in isolation, as well as the particular difficulties of a hybrid model. In Section 3, we describe a working hardware prototype of a hybrid RF/FSO node. In Section 4, we formulate the optimization problem of topology control for hybrid RF/FSO networks. Finally, in Section 5, we present overall assessments and conclusions, closing the planned future trajectory of our research efforts.

2. THE CHALLENGES OF RF, FSO, AND HYBRIDS

2.1 Free Space Optics (FSO) Technology

FSO communications is a line-of-sight technology that uses invisible beams of light to transmit and receive voice, video and data information through the air with a rate up to 1.25 Gbps. FSO operates in the infrared (IR) spectral range—akin to many fiber optics solutions—by using wavelengths near the visible spectrum around 850 and 1550nm (corresponding to 200THz portion) of the spectrum [3, 5]. The Federal Communication Commission (FCC) does not presently require a permit for FSO transmitters, since FSO operates in an unregulated region of the spectrum [43].

FSO signals are transmitted by an infrared laser or LED, and received by high sensitivity receivers at the remote link side [14, 44]. Typically, FSO systems are based on communications links between pairs of free space optical transceivers (transmitter and receiver) that provides full duplex communication links. The optical units use lenses or telescopes, which narrow the light beam and project it toward the receivers. The transmitted light is picked up at the receiver side by a lens, which is connected to a sensitive detector via optical fiber [5, 11, 12, 45]. FSO transceivers can be positioned on a rooftop, at the corner of a building, or indoors behind a building as (See Figure 2). Presently FSO transmission ranges vary between 700 feet to about a mile in a clear, dry atmosphere [11, 46].

In FSO, channel impairments can be caused by fiber attenuation, insertion losses, chromatic dispersion, PMD, or fiber nonlinearities. The attenuation in fiber can be described as the change in signal power over the course of the transmission, and can be defined as: $dP/dz = -\alpha P$, where α is the power attenuation coefficient per unit length [47]. In general, the attenuation of an optical fiber measures the amount of light lost between input and output. Total attenuation is the sum of all losses [48]. Moreover, fiber loss can be caused by the fiber splices and fiber connectors. The fiber splices can be fused or joined together by some mechanical means, with typical attenuation being 0.01–0.1 dB per fused splice and slightly above 0.1 dB per mechanical splice [47]. Chromatic Dispersion occurs when optical pulses are spread out into a much broader temporal distribution than actual optical fiber channel [47, 49]. Another cause of impairments is Polarization Mode Dispersion (PMD). It happens when the polarization unit vector, representing the state of polarization (SOP) of the electric field vector, does not remain stable in practical optical fibers; rather, it changes in a random manner along the fiber because of its fluctuating birefringence [47, 50]. At last, Fiber nonlinearities present a new realm of obstacle that must be overcome. Fiber nonlinearities arise from two basic mechanisms: The most detrimental mechanism arises from the refractive index of glass being dependent on the optical power going through the material. The second mechanism that causes fiber nonlinearities is the scattering phenomena [51].

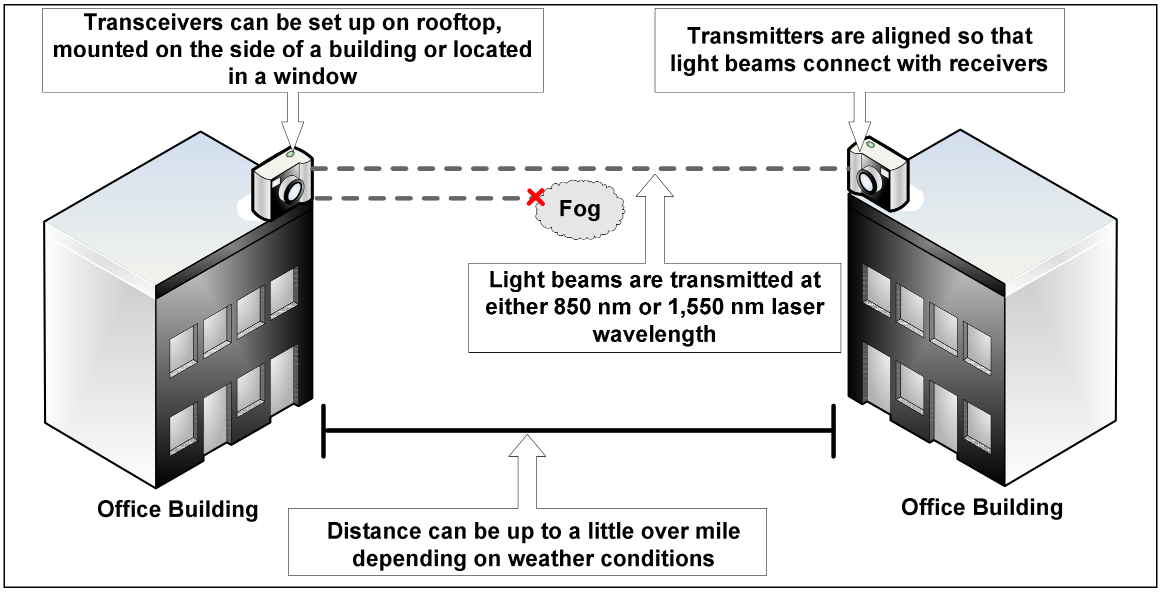

FIGURE 2:FSO connections with line of sight access.

FSO has several advantages over existing wireless or wired communication technologies. As a communication technology enjoys the higher capacity advantages of fiber, so greater data access can be provided. The spatial confinement of each FSO laser beam allows for beams to operate independently, and provides virtually unlimited frequency reuse. FSO is extremely secure, since an adversary cannot incept communications without placing itself in direct path between two FSO points, which is difficult and often detectable (as energy loss) by the legitimate endpoints [1]. Finally, FSO technology supports much more rapid deployment compared to other access technology [9]. In fact, FSO offers significant cost savings since there is no need to make infrastructure changes (e.g. digging up streets to lay cables), since air acts as the transmission medium instead of fiber optics. The installation of FSO systems is cheaper than fiber optics, DSL or cable modem services, and many FSO installations can be completed in a few days [6, 9].

The source of FSO's advantages is also a source of limitations: the air transmission medium. Whenever the medium's condition is unstable or unpredictable, it becomes difficult to manage free space optics transmissions, since volatility in the medium cause disruptions in "line of sight", and thus impact system availability and capacity. The main causes of such disruptions include:

- **Fog**, composed of water droplets, can completely obstruct the passage of light by a combination of absorption, scattering and reflection. This can reduce the power density of the transmitted beam, and therefore decrease FSO link transmission range.
- A**bsorption** decreases the power density of the link and degrades system availability.
- **Scattering** occurs when photons collide with the airborne particles. Even in the absence of energy loss, this results in directional redistribution of beam energy, which, in turn, causes multipath effects.
- **Scintillation**, occurs when light propagates through space which contains sharp temperature variations across different pockets of air. Scintillation causes periodic fluctuations of the signal amplitude, which can lead to a sharp increase in the bit-error-rate of the FSO link.

There are additional secondary challenges faced by FSO systems such as physical obstructions, building sway, rain, snow, and eye safety [1, 3, 5, 11].

While FSO technology has been in use by the military and NASA for almost 30 years, it is still a relatively new technology in civilian telecommunication applications. Recently, it has been considered as a candidate replacement for fiber optics, in solutions seeking to develop a high-speed wireless network access [9, 11].

2.2 Radio Frequency (RF) Technology

RF refers to a number of different technologies, products and industries. Broadly speaking, RF refers to the portion of the frequency spectrum in which radio waves can be generated (resp. received) by driving (resp. detecting) alternating current through an antenna. In RF systems, data is transmitted through air by digital radio signals at a given frequency, typically in the 3kHz to 300GHz range. Such communication can be used to maintain bi-directional, online radio connection between a mobile telephone and an antenna host for example.

RF technology has the advantage of being wireless, and thus requires no cable deployment expenses to provide communication access. This instant accessibility also provides a timesaving in the deployment process. Also, the real-time accuracy of RF is high (>99%) and can be considered a general advantage.

On the other hand, the development of technologies based on RF communications is hindered by regulation in the assignment of radio spectrum bands by the FCC and National Telecommunications and Information Administration (NTIA). As of today, the FCC has allocated frequencies between 9 kHz and 275 GHz, with the highest bands reserved for radio astronomy and satellites [3, 52].

2.3 RF vs.FSO

RF and FSO are two different wireless technologies and there is no direct *competition* between them. In what follows, we summarize the main differences between them:

A) *Throughput.* The major advantage of FSO is its high throughput compared to RF. At present, FSO can provide a throughput of 1.25Gbps for links of up to a kilometer or more. In contrast, wireless RF technologies such as 802.11a provide link throughput of tens of Mbps with distances of tens of meters. Although Ultra Wide Band (UWB) technology can provide a throughput of hundreds of Mbps, it usually drops to levels lower than even 802.11a at long ranges [11, 14, 15].

B) *Deployment Costs.* FSO links have low cost of deployment compared to fibers, and system installation can be completed within few days [23].

C) *Reliability.* FSO link traffic can experience disruptions due to atmospheric turbulence, while RF links are largely immune to such effects [17]. Low deployment cost makes FSO easy to maintain in the event of equipment failures, and thus suitable as components in a high reliability backbone for military applications and MANs.

D) *Security.* RF link transmissions can be intercepted or detected by 3rd parties. This makes RF unsecure without addition time and energy expenditures [18] in the form of encryption algorithms. In comparison, FSO technology is extremely secure, even without encryption overlays because it uses a directional narrow beam point-to-point line of sight transmission, whose interception is easy to detect. A laser FSO at 1550nm offers an excellent wireless transmission solution and provides the highest possible level of physical layer security [19, 20].

E) *Availability.* Link availability for RF is frequently above 99.999%. Unfortunately, performance level for FSO may vary from one area to another depending on the atmospheric conditions [36]. Effective FSO transmission range can thus vary from more than 700 feet up to about a mile in a clear, dry atmosphere [8], though ensuring carrier-class availability often requires that link length be limited to 200–500 meters [6].

F) *Frequency Bands.* RF systems operate in frequency bands between 3kHz and 300GHz. Some frequencies in this spectrum range are regulated and assigned by the FCC [21]. In contrast, FSO systems operate in frequencies around 200THz, which presently requires no RF spectrum licensing [22].

G) *Eye Safety.* RF signals are relatively harmless to the human eye. In comparison, FSO signals can damage the cornea and lens of the eye, particularly if transmissions are in the visible or near infrared spectrum regions[1] (100-1,200nm).

H) *Calibration:*FSO systems require beam pointing, acquisition, and tracking, since optical transceiver must be aligned to each other for communication to take place. The precision tolerances mandated in the alignment process depend on the link power budget and the design of transmitters and receivers [1]. In contrast, in RF systems, there is no special alignment process required between transmitter and receiver, since transmission is radial and does not operate via line of sight [18].

2.4 Major Technical Challenges in Hybrid RF/FSO

By hybridizing RF and FSO technologies intelligently, we seek to address the needs of current applications in a manner that supersedes what is achievable using a single technology alone. Doing so, however, requires surmounting certain technical challenges. In this section we describe the three major technical challenges: (A) Pointing, Acquisition and Tracking, (B) Routing and Path

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[1] This is a compelling reason for selecting the longer 1550nm wavelength as the basis for FSO Systems.

Protection, and (C) Topology Control. We will also present currently proposed solutions for each of these challenges.

A) Pointing Acquisition and Tracking

One challenge faced in real FSO deployments is the necessity to maintain Line Of Sight (LOS) between sender and receiver during transmission using the FSO channel. This problem is called the “Pointing-Acquisition-Tracking” (PAT) process. We do not consider PAT to be a limitation or disadvantage, since several researchers have developed adequate solutions to this problem using different techniques. Nevertheless, PAT is at present, an active research area. In considering hybridized RF/FSO schemes where nodes are mobile, the PAT process gets even more difficult.

Derenick et al. proposed a hierarchical PAT system in which they used a vision-based system to maintain LOS [14]. The system assumes prior knowledge regarding the initial position of each FSO node and its partner receiver. In addition, both sender and receiver need to refer to a relative “origin” to interpret position and orientation updates. The authors accomplished this using a GPS system and inclinometer sensors. The alignment process is carried out using feedback from a high zoom camera system. The dependency on a GPS system makes this approach restricted for large-scale outdoor applications.

Akellaet. al, the authors proposed an omnidirectional spherical FSO transceiver to maintain LOS in hybrid RF/FSO MANETs [24] as illustrated in Figure 3. The surface of this sphere is covered with FSO transceivers, which contain LEDs and photodetectors. When two mobile FSO nodes in this design move away from each other the existing LOS link will be lost and a new one will be established. The omnidirectional FSO transceiver is a promising approach to the alignment problem in mobile environments. Unfortunately, current hardware implementations are not fast enough to switch the beam to another FSO channel without significant breaks in connectivity—especially when the environment is highly dynamic one (e.g. a tactical setting). Omnidirectional FSO transceivers may also sacrifice some covertness if movement is discontinuous, and the process of repairing broken optical channels is not done carefully.

Nichols proposed a framework using a dynamic RF/FSO staged acquisition technique [21]. The proposed framework decomposes PAT into three major stages as illustrated in Figure 5: A very wide RF signal is sent by the sender in order to identify the location of the FSO receiver. After locating the FSO receiver object, a wide FSO beam is sent by the sender to establish the FSO link. Finally, the sender and receiver narrow the FSO beam width down, to meet the QoS requirement. This approach also seems a promising solution to solve PAT problem in dynamic environment. Unfortunately, there has been no implementation or field test of this proposal[2] to date.

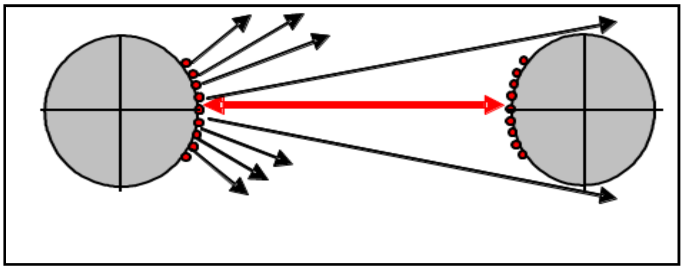

FIGURE 3:FSO connections with line of sight access.

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[2] No hardware implementation of the proposed system exists as of the writing of this article.

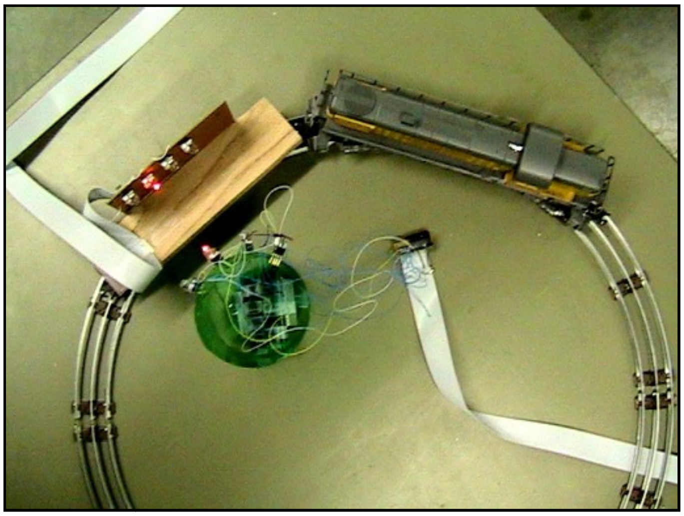

FIGURE4:3D-Omnidirectional spherical FSO transceiver [24]

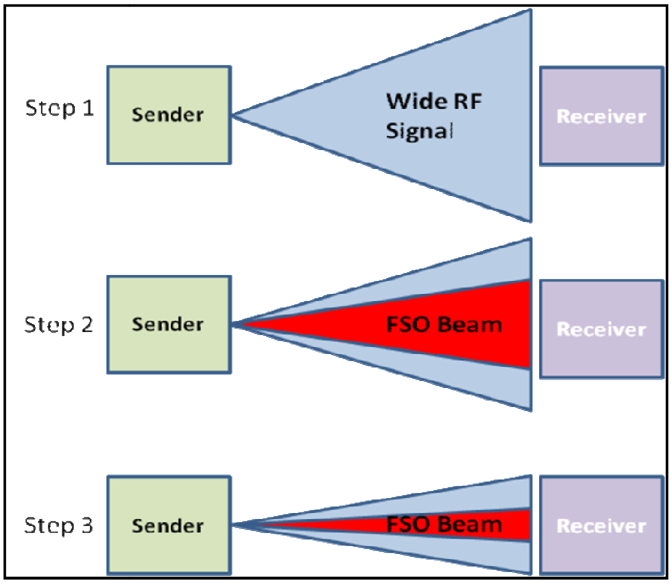

FIGURE 5: Dynamic RF/FSO staged acquisition technique [21]

B) Routing and Path Protection in Hybrid RF/FSO

The disparate (and time-varying) natures of the RF and FSO channels make routing a difficult problem in hybrid RF/FSO networks. Kashyap and Shayman introduced a routing framework for hybrid RF/FSO networks that relies on the assumption that RF links should have lower backbone traffic demand compared with FSO links [17]. Based on this assumption, they introduced a concept called “critically index” which determines the fraction of each traffic profile entry. A path is then computed for each traffic profile entry using the shortest widest path (SWP) algorithm, which is implemented as an extension of the OSPF routing protocol [25].

The fact RF links are more reliable than FSO channels led several researchers to consider using the RF channel for path protection in hybrid RF/FSO networks. For instance the Kashyap et al proposed a joint topology control and routing framework where the RF links serve to provide instantaneous backup to traffic in hybrid RF/FSO networks when FSO links are degraded [27]. Their proposal does not treat the RF channel as “just an additional wavelength”, since the failure of the RF channel is not a single point failure as the case in the wired optical links[3]. Because of this fact, the problem cannot be solved using classical path protection schemes developed for optical networks (e.g. see Ramamurthy and Mukherjee [26]) and requires the development of new strategies.

C) Topology Control

The disparate (and time-varying) natures of the RF and FSO channels also make topology control a difficult problem in hybrid RF/FSO networks. Topology control in traditional pure-RF networks has been extensively studied. Examples of objectives considered have been, for example, how to adjust the power levels to have connected network yet use the minimum possible total power; or, how to reduce interference to meet some specific QoS requirements, [28, 29, 30] etc. Very limited research has been carried out in the area of topology control for hybrid RF/FSO.

Baskaran et al. studied the ability to provide topology reconfiguration according to changes in links capacities and traffic demands in RF/FSO networks [31]. The authors developed a heuristic for finding a topology configuration with the minimum packet drop rate. The heuristic cost of the packet drop rate includes factors reflecting both the link congestion cost and the packet drops that occur while the topology reconfiguration process is underway.

In section 4, we will present an integer linear program (ILP) model to solve the topology control problem, based on adapting and adjusting the transmission power and the beam-width of individual nodes according to Quality of Service (QoS) requirements. Our main focus will be to meet QoS requirements in terms of end-to-end delay and throughput jointly.

3. HYBRID RF/FSO PROTOTYPE

In our research lab, we were able to implement a hybrid RF/FSO prototype. To accomplish this objective, the development work was carried out in the following steps:

1) Implement a real system to transmit and receive data over one FSO channel.
2) Enhance the FSO transceiver to be able to operate over three FSO channels.
3) Implement an RF transceiver.
4) Improve the RF transceiver to be able to operate over three RF channels.

Develop and propose a hybrid system that combines systems produced in steps (2) and (4) to provide RF and FSO data access.

3.1 Single-channel FSO System Design

The central element of an FSO design is to have a line of sight data transmission. FSO technology pioneers such as LightPointe or fSONA offer a wide variety of FSO transceivers. In this section we design and implement a simple prototype FSO system that has the capability to send and receive data over a single FSO channel. We found that a simple infrared circuit can achieve this adequately, since FSO technology operates in the IR spectrum. The main difference between the industrial FSO transceivers and our infrared circuit is the transmission range. In industrial FSO laser transceivers, the transmission range can reach up to 1 mile in clear atmospheric conditions, while it is limited to just a few meters in the infrared. However, coverage distance is not a critical issue at this point since our goal is a prototype that will be used to test the signals transmitted and received.

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[3] Take for example, the interference in RF area, which can hit all RF channels in that interference range and not only a single RF channel.

The requirements and the IC components involved in our implementation of this system are as follows:

- A PC workstation
- Serial port interfacing Cable
- A software or a program that can transmit and receive data at the same time over the serial cable
- UART MAX 232 Dallas
- MCP 2120
- A Timer or a crystal oscillator TLC555
- MAX 3120
- Infrared LED and photodiode

Serial Port Interfacing

The system was designed to read and write data from and to a PC workstation. One of the most common ways to interface circuits with PCs is through serial port communication. In our prototype, a simple JAVA application was developed to send and receive data over serial ports using the RS-232 cable.

UART MAX232 Dallas

The MAX232 chip is simple a driver/receiver that converts TTL/CMOS input levels into TIA/EIA-232-F levels and vice versa. In our design, it acts as a bridge to carry data to or from the RS232 cable to or from the IR transceivers [32].

MCP 2120

This device is an infrared encoder/decoder, which is placed between a UART and an infrared (IR) optical transceiver where the data received from a standard UART is encoded (modulated) and then sent as electrical pulses to the IR Transceiver. When the IR Transceiver receives data, it sends it as electrical pulses that are decoded (demodulated) by the MCP2120. This modulation and demodulation method is performed in accordance with the IrDA standard. The MCP supports both hardware and software baud rate selection. In this design, we selected hardware baud rate by tying the pins BAUD2, BAUD1 and BAUD0 to the values 1,0,0 respectively. By doing so, the baud rate by the MCP 2120 was Fosc/64 where Fosc is the frequency generated by an external timer or a crystal oscillator. It is necessary to match the baud rates at the MCP2120 and the RS 232 serial cable so that the system works properly [33].

A TLC555 timer or a crystal oscillator

Since the MCP 2120 encoder requires an external timer or oscillator to generate the required baud rate, a TLC555 timer was used to supply the MCP2120 with the appropriate frequency [34]. The TLC555 timer was sat up to generate a frequency of 6037.66 KHz which made the MCP 2120 provide a baud rate of (Fosc/64) = (6037.66 KHz/64) = 9433 bps. Also, a 1.84 MHz crystal oscillator was used instead of the TLC555 timer to supply the MCP2120. The generated baud rate was 1.84 MHz/64 = 28.8 Kbps.

MAX 3120

This is an 8-pin chip that operates as an IR transceiver. With this chip and few more components—an LED, a photodiode, capacitor, and a few current-setting resistors—the Infrared application design is complete and ready to send and receive data over one channel [35].

Infrared LED and Photodiode

We used one IR LED transmitter and one photodiode detector to transmit and receive infrared data over one channel. The chosen LED has a wavelength peak emission of 950nm and the photodiode has a spectral bandwidth range of 620nm to 980nm.

As illustrated in Figure 6 and Figure 7, the system was built so that it can transmit and receive data at the same time. The same PC workstation can transmitted signals and receive them. To do so, we developed a simple JAVA program that uses threads to continue listening for the user commands while it keeps reading any data that may have been received by the serial port.

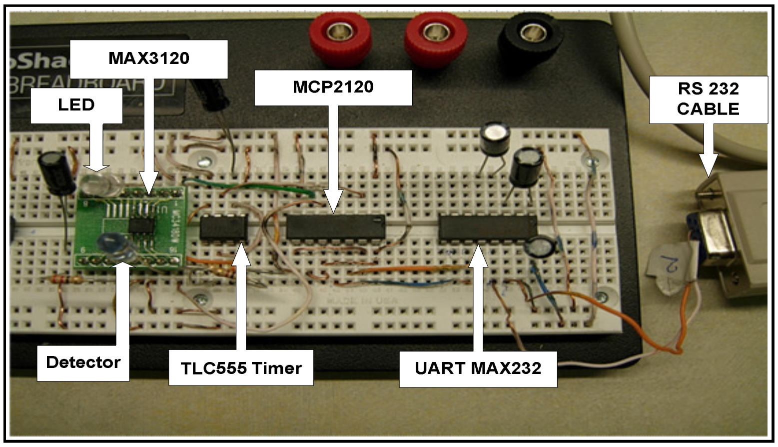

FIGURE 6:IR transceiver circuit for 1-channel communication.

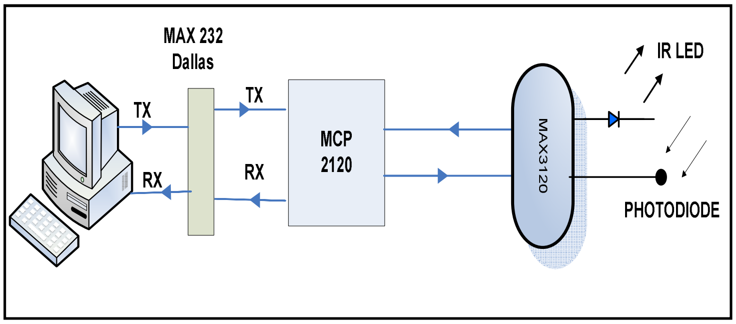

FIGURE 7: Block diagram of the 1-channel IR transceiver.

The system was tested, by sending and receiving English, encoded as a stream of 8-bit ASCII characters. The transmission was not 100% accurate, especially when any object obstructed the line of sight between the LED and the photodiode. In fact, this was expected because FSO and infrared are line of sight technologies and, therefore, data transmission is sensitive to alignment/obstructions between the transmitter and receiver[4].

3.2 Multi-channel FSO System Design

The motivation behind transmitting infrared data over three channels is to improve system performance by providing more redundant channels for transmission, and thus higher reliability and availability of the communication system. In this design we added a PIC microcontroller to do FSO channel duplication. The PIC can take input on one pin and duplicate it to any of the three independent channel circuits, thereby providing the ability to do smart multiplexing/de-multiplexing to select based on the best quality of service channel or other global coordination logistics. The three channel circuits must each operate on a different wavelength to ensure concurrent multi-channel transmission can really provide an increase in reliability.

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[4] Other reasons for the data loss might come from the small difference in the baud rate. The serial cable has a set of predefined baud rates at which it transmits the signals. These rates were not exactly matching the baud rates at the MCP2120 encoder/decoder.

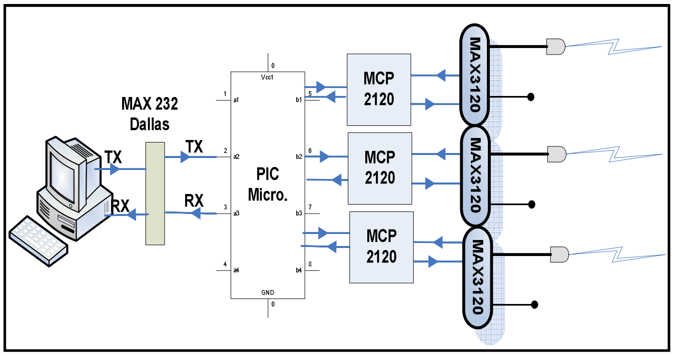

FIGURE 8: Block diagram of 3-channel IR transceivers.

This system is illustrated in Figure 8. As seen, it is composed of one UART, three infrared encoders/decoders and three transceivers. Also, there are three LEDs and three photodiodes, each of which operates in different wavelengths.

3.3 Single-channel RF System Design

RF systems can be built over different architectures and implementations, depending on the underlying technology used (e.g. Bluetooth, ZigBee, OFDM or any other circuit that works on the RF frequency band). The one-channel RF transceiver we implemented works on the 434 MHz frequency band; it has been tested by sending and receiving English ASCII characters using a test jig that is very similar to the unit tests of the FSO circuit. The components required to build this transceiver were:

- A PC workstation
- Serial port interfacing Cable
- A software or a program that can transmit and receive data at the same time over the serial cable
- UART MAX 232 Dallas
- MCP 2120
- TLP434A Transmitter
- RLP434A Receiver
- Two 400 MHz RF antennas

The first four components listed above were used in the RF system identically to their manner of use in the FSO transceiver—namely to send data to and receive data from the workstation. In place of IR LED and photodiode, two RF modules used to send and receive the RF signals: these were the TLP434A and RLP434A, provided by LAIPAC [36]. The TLP434A module is an Ultra Small Wireless Transmitter that is ideal for remote control projects or data transfers to a remote object via the 434MHz frequency band. The RLP434A module is a Compact Radio Receiver (RF) that works directly with the TLP434A transmitter over the 433.92Mhz frequency band. Each of the two modules requires a 400 MHz antenna for transmitting and receiving the signals [37]. The implementation is illustrated in Figures 9 and 10.

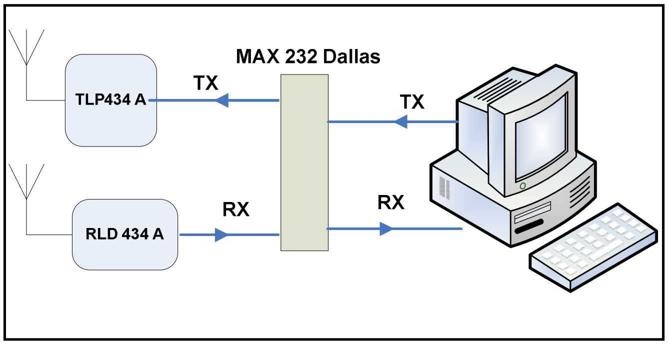

FIGURE 9: One channel RF transceiver block diagram

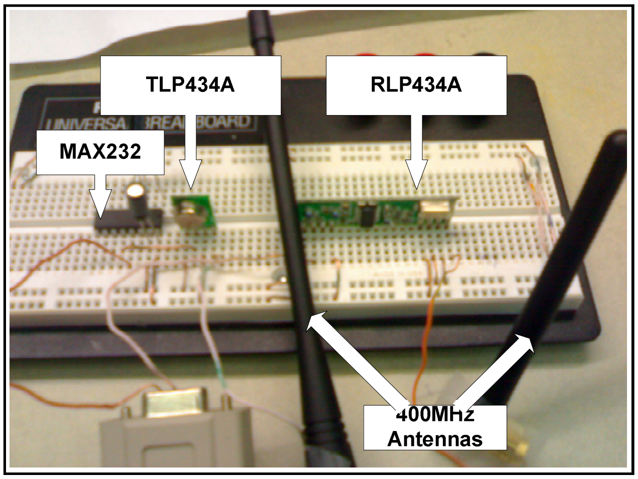

FIGURE 10: Single RF transceiver system

3.4 Multi-channel RF System Design

The single RF channel system was extended to provide transmission over three different RF channels, each based on a different frequency band. The motivation behind this was, once again, to improve the reliability and availability of the channel. This revised system used the three LAIPAC RF modules: TLP434A/RLP434A, RF900DV and RF2400DV to provide frequency bands of 434 MHz, 900 MHz and 2.4 GHz successively [38, 39]. A PIC microcontroller was also used in this design to distribute the single input data channel into three and to offer the ability to do smart multiplexing/de-multiplexing based on the best quality of service channel or other global coordination logistics.

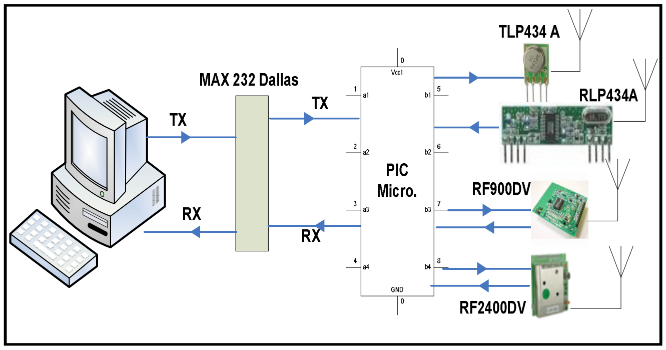

FIGURE 11: Three RF transceivers system block diagram

The proposed hybrid FSO/RF system illustrated in Figure 12 combines the two orthogonal architectures: FSO multi-channel (see Section 3.2 above) and RF multi-channel (see Section 3.4 above). Such a hybrid system offers FSO connectivity over three different wavelengths and reliable RF wireless communication over three different frequency bands. This prototype may not clearly state how hybrid RF/FSO networks exploit the strengths of each technology. But, such system increases the overall bandwidth via FSO, as well as high availability in dense fog or in bad atmospheric conditions where the RF transceiver can be used as a backup channel. The architecture provides a highly reliable link since it concurrently operates multi-channel communication links over FSO and RF, over different wavelengths and frequency bands.

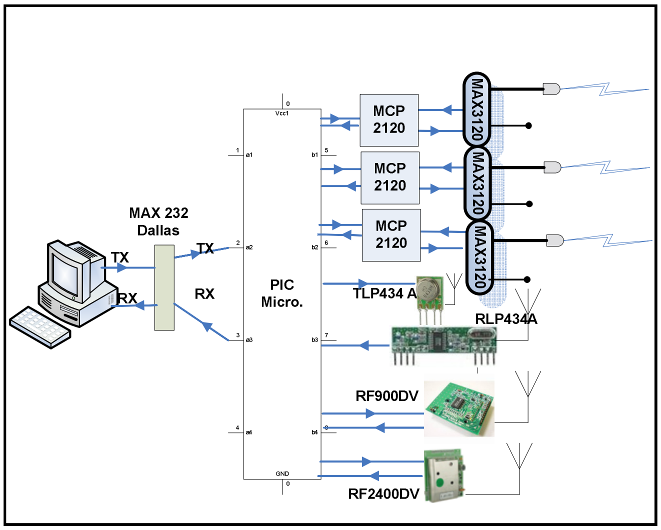

FIGURE 12:A hybrid FSO/RF system architecture

4. ILP FORMULATION OF THE TOPOLOGY CONTROL PROBLEM IN HYBRID RF/FSO NETWORKS

In this section we formulate the topology control problem for hybrid RF/FSO wireless mesh networks, as an integer linear programming (ILP) problem. Informally, we seek to construct a robust topology by minimizing the transmission power, adapting the beam-width, and selecting different channels—all in a manner that allows us to meet specified throughput and end-to-end delay requirements.

We make the following assumptions: First, that the network topology is a mesh with directed links. Second, that each node is both an RF and an FSO transceiver. Finally, we assume that RF transceivers are omnidirectional, while FSO transceivers are directional.

We begin with our **resources** and their **limitations**: Aset of mobile nodes *V*. For each node $i \in V$, we have its location, and the number of RF and FSO transceivers present. Let T_i be the set of transceivers at node *i*. For each transceiver *t* in T_i we have: its maximum capacity *C_MAX*, its sensitivity *S*, its diameter *D*, its maximum angular beam width, and its maximum transmission power level. We consider a discrete set of possible transmission powers *P*, and a discrete set of possible (angular) beam openings Φ.

Next, we state our **constraints**: A set of source-destination pairs SD, whoseQoS is to be guaranteed. For each $(s,d) \in SD$, we have the maximum delay, $H_{(s,d)}$:Maximum delay, and the minimum acceptable throughput $Th_{(s,d)}$.

In the preprocessing step, we construct a possible network topology G = (V, E). Our objective is to select an optimal construction based on our ILP formulation. The links in a given graph can be enumerated as:

- $l_{i,j,t}^{p,\theta_t,\theta_r}$: For a given transmission power p, transmitter beam-width θ_t, and receiver beam-width θ_r, $l_{i,j,t}^{p,\theta_t,\theta_r}=1$ if there is a *link(i,j,t)* available from node *i* to node *j* using transceiver *t*; otherwise $l_{i,j,t}^{p,\theta_t,\theta_r}=0$. The *link (i,j,t)* is said to be available if node *j* is inside the coverage area of node *i* using transceiver *t*. This can be verified easily by calculating the transmitter's maximum range, and determining the coverage area based on a scaled sector shape (for FSO channels), or a scaled circle shape area (for RF channels). If t is an FSO transceiver, then for *link(i,j,t)* to be considered available it must be verified that there is a line of sight between the transmitter and the receiver.

- $BER_{i,j,t}^{p,\theta_t,\theta_r}$: For a given transmission power p, transmitter beam-opening θ_t, and receiver beam-opening θ_r, $BER_{i,j,t}^{p,\theta_t,\theta_r}$ represents the bit error rate on *link (i,j,t)*.

- $B_{i,j,t}^{p,\theta_t,\theta_r}$: For a given transmission power p, transmitter beam- opening θ_t, and receiver beam-opening θ_r, $B_{i,j,t}^{p,\theta_t,\theta_r}$ represents the bandwidth of *link(i,j,t)*:

$$B_{i,j,t}^{p,\theta_t,\theta_r}=\frac{B\max_{i,t}}{\sum l_{i,j,t}^{p,\theta_t,\theta_r}}$$

  where $B\max_{i,t}$ is the bandwidth of transceiver *t* at node*i*.

We are now ready to formalize the ingredients of the ILP, namely the variables, objective function, and constraints.

We introduce the following Boolean **variables**:

- $l_{i,j,t}^{s,d}$: Boolean variable, $l_{i,j,t}^{s,d}=1$if the path of (s,d) connection pair uses *link(i,j,t)*; otherwise $l_{i,j,t}^{s,d}=0$.
- $g_{i,j,t}^{p,\theta_t,\theta_r}$: Boolean variable selector, $g_{i,j,t}^{p,\theta_t,\theta_r}=1$ if $l_{i,j,t}^{p,\theta_t,\theta_r}$ is selected to construct the topology; otherwise $g_{i,j,t}^{p,\theta_t,\theta_r}=0$.
- $x_{i,t}^{p}$: Boolean power indicator variable. $x_{i,t}^{p}=1$ if transceiver *t* at node *i*is transmitting using power *p)*; otherwise $x_{i,t}^{p}=0$.

The **objectivefunction** is to minimize transmission power by all nodes in the network.

$$Min\left(\sum_{\mathrm{i,t,p}} p.\,x^{p}_{i,t}\right) \quad (1)$$

Finally, we describe the constraints of the ILP. These fall into various classes: Routing constraints, bandwidth constraints, throughput constraints, power constraints, beam opening constraints, alignment constraints, and selector constraints.

Routing Constraints.To ensure that each (s,d) pair is routed:

$$\sum_{t}\sum_{j} l^{(s,d)}_{i,j,t} - \sum_{t}\sum_{j} l^{(s,d)}_{j,i,t} = \begin{cases} 1 \text{ if } \mathrm{s=i} \\ -1 \text{ if } \mathrm{d=i} \\ 0 \text{ otherwise} \end{cases} \forall i \in V \text{ and } (s,d) \in SD \quad (2)$$

and that a single route is assigned for a given (s,d) pair:

$$l^{(s,d)}_{i,j,t} \leq \sum_{(p,\theta_t,\theta_r)} l^{p,\theta_t,\theta_r}_{i,j,t}.\,g^{p,\theta_t,\theta_r}_{i,j,t} \quad \forall i,j \in V, t \in T_i, (s,d) \in SD \quad (3)$$

Delay Constraint. To ensure that the number of hops in the selected route doesn't violate the delay requirement:

$$\sum_{i,j,t} l^{(s,d)}_{i,j,t} \leq H_{s,d} \quad \forall (s,d) \in SD \quad (4)$$

Throughput Constraints. To ensure that throughput requirements are met:

$$\sum_{(s,d)} l^{(s,d)}_{i,j,t}.Th_{(s,d)} \leq \sum_{(p,\theta_t,\theta_r)} B^{p,\theta_t,\theta_r}_{i,j,t}.(1 - BER^{p,\theta_t,\theta_r}_{i,j,t}).\,g^{p,\theta_t,\theta_r}_{i,j,t}$$
$$\forall i, j \in V, t \in T_i \quad (5)$$

Power Constraints. To ensure that power indicator $x^{p}_{i,t} = 1$ when transceiver *t* at node *i*is transmitting using power *p.*

$$\sum_{(j,\theta_t,\theta_r)} g^{p,\theta_t,\theta_r}_{i,j,t} \leq N x^{p}_{i,t} \quad \forall \mathrm{p} \in \mathrm{P}, \forall \mathrm{t} \in \mathrm{T_i}, \forall i \in V \quad (6)$$

$$\sum_{(j,\theta_t,\theta_r)} g^{p,\theta_t,\theta_r}_{i,j,t,p} \geq x^{p}_{i,t} \quad \forall \mathrm{p} \in \mathrm{P}, \forall \mathrm{t} \in \mathrm{T_i}, \forall i \in V \quad (7)$$

where*N* is the number of nodes.

Selector Constraints. To ensure that a single value has been selected for power and beam width at each node:

$$\sum_{(j,p,\theta_t,\theta_r)} g_{i,j,t}^{p,\theta_t,\theta_r} \leq 1 \quad \forall i \in V, \forall t \in T_i$$
$$\text{where t is an FSO tranceiver} \qquad (8)$$

$$\sum_{(j,p,\theta_t,\theta_r)} g_{j,i,t}^{p,\theta_t,\theta_r} \leq 1 \quad \forall i \in V, \forall t \in T_i$$
$$\text{where t is an FSO tranceiver} \qquad (9)$$

$$\sum_{(p,\theta_t,\theta_r)} g_{i,j,t}^{p} \leq 1 \quad \forall i, j \in V, \forall t \in T_i$$
$$\text{where t is an RF tranceiver} \qquad (10)$$

Beam-opening Constraints. To ensure that transceiver *t* at node *i*is using the same beam opening during transmission and reception.

$$\sum_{(p_x,\theta_t,\theta_r)} g_{i,j,t}^{p_x,\theta_t,\theta_r} + \sum_{(p_y,\theta_m,\theta_n)} g_{j,i,t}^{p_y,\theta_m,\theta_n} \leq 1$$
$$\text{When}\, \theta_n \neq \theta_t \; \forall i, j \in V, t \in T_i, \forall \theta_t \in \Phi \qquad (11)$$

Alignment Constraints. To ensure that sender and receiver are in each other's transmission cones:

$$\sum_{(p,\theta_r)} g_{i,j,t}^{p,\theta_t,\theta_r} + \sum_{(p,\theta_m,\theta_n,l)} g_{l,k,t}^{p,\theta_m,\theta_n} \leq 1 \quad \text{When}\, \theta_n \neq \theta_t,$$
$$\forall t \in T_i, \forall \theta_t \in \Phi, \forall i, j, k = i \text{ or } k \text{ in line of sight of } i \text{ and } j. \qquad (12)$$

	(Link , Transceiver)	Transmitted Power (mW)	Beam Opening (mrad)	Total Consumed Power
ILP	(1➔2,0)	5	-	35
	(1➔5,0)	5	-	
	(2➔5,2)	5	80,80	
	(3➔1,1)	10	80,240	
	(3➔2,3)	5	80,80	
	(4➔3,0)	5	-	
	(5➔4,1)	5	80,160	

TABLE 1: Traffic used to design the topology

The complexity of any ILP problem depends on the number of variables and constraints in that problem. In the proposed formulation, the factors that determine the number of variables and constraints are the number of nodes (N), the number of transceivers (T), the number of source destination pairs (SD),

	Src	Dst	Route	Selected channels
ILP	1	2	1➔2	0
	1	5	1➔5	0
	2	4	2➔5➔4	2➔1
	2	5	2➔5	2
	3	1	3➔1	1
	4	3	4➔3	0
	4	2	4➔3➔2	0➔3
	5	4	5➔4	1

TABLE 2: Transmitted power and beam opening optimal solution using the proposed ILP formulation.

the transmission power granularity (*P*), and the beam width granularity (θ). The following two equations provide the number of variables and constraints involved in the ILP problem.

$$W = N[(N-1)(SDT + P(1+T\theta^2)) + TP], \quad \text{where } W \text{ is the number of variables} \quad (13)$$

$$Z = N(N-1)[TSD + 2T + (T-1)\theta] + N[SD + 2PT + 2(T-1)] + SD, \quad \text{where } Z \text{ is the number of constraints.} \quad (14)$$

Request	S	D	Throughput (Mbps)	Delay
1	1	2	5	1
2	1	5	5	1
3	2	4	100	2
4	2	5	100	1
5	3	1	250	1
6	4	3	5	1
7	4	2	5	2
8	5	4	100	1

TABLE 3: Routing and channel selection for each requested connection using the proposed ILP.

4.1 ILP Results

We provide an experimental assessment for the ILP formulation of the topology control problem in hybrid RF/FSO mesh networks. In these experiments, we assumed that the capacity of FSO channel is 500 Mbps, the capacity of RF channel is 50 Mbps, the FSO receiver sensitivity is -43dBm, the RF receiver sensitivity is -84dBm, and the maximum beam opening is 240 mrad.

Table 1 presents the matrix of source-destination connection pairs and the desired QoS for each. Tables 2 and 3 (and Figure 13) provide the route found by the ILP solver. The solution uses low power (by adjusting the beam openings and transmission powers of carefully selected channels) and yet meets the joint throughput and end-to-end delay requirements. The solution obtained had a total power consumption of 35mW.

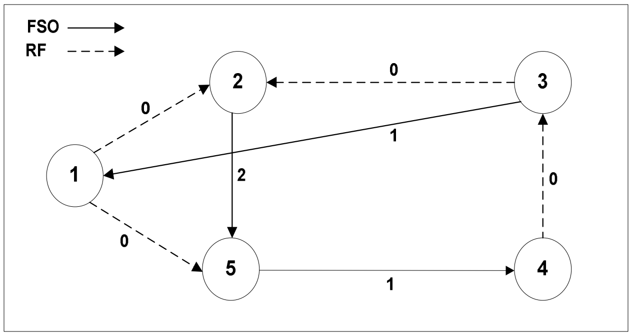

FIGURE 13: Topology generated by ILP solution

5. CONCLUSION AND FUTURE WORK

We presented the strengths and shortcomings of RF and FSO, and the challenges (and opportunities) facing researchers who seek to make hybrid RF/FSO communications a viable technology. We described a prototype implementation for a transceiver node in a hybrid RF/FSO system, illustrating the feasibility and accessibility of the approach. Our hardware was composed of readily available parts: a PIC microcontroller, RF transceivers, IR LEDs and photodiodes, and a few other IC components. The system was extended to provide selectable multichannel multi-frequency capabilities, and was successfully tested and found to be capable of sending and receive English text in 8-bit ASCII encoding. Based on the characteristics suggested by this prototype, we developed a mathematical model of the topology control problem for hybrid RF/FSO networks, as an integer linear program (ILP). We showed that this formulation, when presented to an ILP solver, is capable of adaptive adjustment of transmission power levels and beam openings, in a manner that minimizes total power consumption while satisfying end-to-end quality of service constraints.

Hybrid RF/FSO has the potential to be a “green solution” since it provides a secure, rapidly deployable communication infrastructure with reduced total energy consumption. The hardware prototype and the topology control solution we presented for hybrid RF/FSO can be readily extended and are an important first step in this direction. The hybrid RF/FSO approach could prove especially beneficial in challenging areas such as battlefield environment, intelligent transportation systems, and telesurgery.

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