Prototyping Multi-Transceiver Free-Space-Optical Communication Structures

Abdullah Sevincer*, Mehmet Bilgi*, Murat Yuksel* and Nezih Pala**
*University of Nevada - Reno, CSE Department
** Florida International University, ECE Department
asev@cse.unr.edu, mbilgi@cse.unr.edu, yuksem@cse.unr.edu, npala@fiu.edu

***Abstract*—Wireless networking has conventionally been realized via radio frequency (RF) based communication technologies. However, the capacity of these networks are limited by the availability of the RF spectrum. Free-Space-Optical (FSO) communication has the potential to deliver wireless communication links at optical-level speeds. Although it has the advantage of high-speed modulation, maintenance of line-of-sight (LOS) between transceivers during an on-going transmission is an important issue since FSO transmitters are highly directional. In this paper, we present a prototype implementation of such multi-transceiver electronically-steered communication structures. Our prototype uses a simple LOS detection and establishment protocol and assigns logical data streams to appropriate physical links. We show that by using multiple directional transceivers we can maintain optical wireless links with minimal disruptions that are caused by relative mobility of communicating nodes.**

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

I. Introduction

The capacity gap between RF wireless and optical fiber (wired) network speeds remains huge because of the limited availability of RF spectrum [1]. Though efforts for an all-optical Internet [2]–[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 (Multiple Input-Multiple Output) [5]. To achieve high-speed wireless point-to-point communications, free-space-optical (FSO) communication has received attention particularly for high-altitudes, e.g., space communications [6], building-top metro-area communications [7], [8] and interconnects made of expensive and sensitive materials [9], [10]. Main focus of these efforts has been on reaching *long* (i.e., $\sim$kms) communication distances with *highly expensive* FSO components (e.g., lasers) with sensitive mechanical steering technologies.

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 can be 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 laser diodes), offer highly directional beams for spatial reuse and security (1-10 microrad beam spread), and operate in large swathes of unlicensed spectrum amenable to wavelength-division multiplexing (infrared/visible). To counteract these numerous advantages, FSO requires clear line-of-sight (LOS) and LOS alignment. 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 wavelength used (aerosols and fog).

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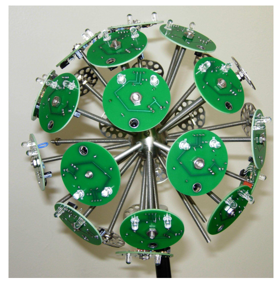
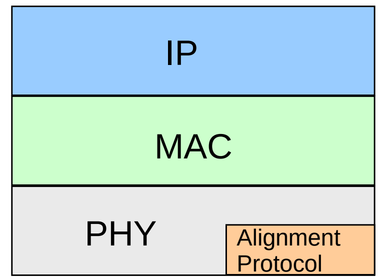


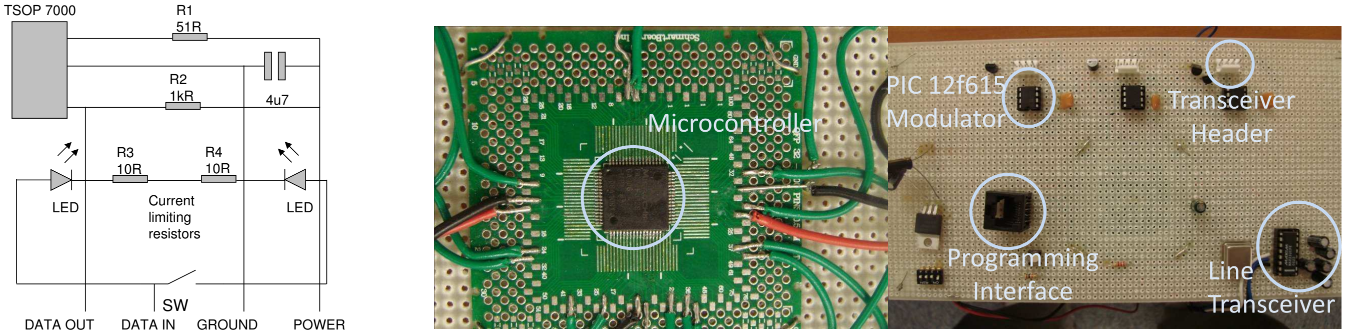
(a) Picture of prototype optical antenna.



(b) Default placement of alignment protocol in protocol stack.

Fig. 1. 3-D optical antenna design and architecture.

Recent work showed that [11]–[13] FSO mobile ad-hoc networks (FSO-MANETs) can be possible by means of "optical antennas", i.e., FSO spherical structures like the one shown in Figure 1(a). 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 (e.g., LED and photo-detector pairs). In this paper, we present a prototype of such a spherical FSO structure with multiple transceivers and its performance. Unlike the traditional mechanical steering mechanisms for LOS management, we use a simple handshaking protocol to "electronically steer" the LOS alignment onto the correct transceiver. We provide proof-of-concept experiment results showing feasibility of achieving optical wireless link over such multi-transceiver structures.



(a) Transceiver circuit schematic.

(b) Controller circuit front and rear view

Fig. 2. Picture of transceivers and schematic of transceiver circuit.

The rest of the paper is organized as follows: In Section II and III we give the literature review for FSO networks and our approach for multi-element FSO nodes respectively. In Section IV, we describe our prototype including transceiver, controller circuit and discuss the alignment protocol employed to establish LOS alignments using multi-element antennas. In Section V we present experimental results. We discuss our conclusions and future work in Section VI.

II. 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 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 [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 network, because of their high throughput capacity.

This kind of last mile application eliminates the need to lay cable, especially in geographically challenging environments while serving a large number of end nodes, each with little bandwidth requirements. Various techniques have been developed for stationary deployments of FSO to tolerate small vibrations [14], swaying of the buildings and scintillation, using mechanical auto-tracking [15]–[17] or beam steering [18].

Employment of FSO communication in indoor environments has been done mainly by using diffuse optics [19]–[21]. 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. Our work showed that using transmitters with large angles increases the interference among transceivers, thus, makes alignment and data transfer impossible. This will cause more issues when we attempt to deploy multiple transceivers on a spherical structure.

The idea of using multiple elements/transceivers in FSO communication has been used in interconnects [9], [22]–[24], 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. 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.

III. Multi-element Spherical FSO Nodes

Figure 1(a) shows the general concept of a spherical surface being covered with FSO transceivers. Our design of optical antenna is based on two principles; (i) *spatial reuse and angular diversity* via directional transceivers tessellated on the surface of the spherical node and (ii) an *alignment protocol* that establishes alignment of two transceivers in line-of-sight of each other. Contrary to the traditional mechanical steering mechanisms to manage LOS alignment, our alignment protocol can be implemented by simple electronics, which we call "electronic steering". Essentially, we use a simplified 3-way handshake protocol to establish alignment between transceivers in LOS of each other. Such an alignment protocol delivers quick and automatic hand-off of data flows among different transceivers while achieving a virtually omni-directional propagation and spatial reuse at the same time [12], [25].

The main purpose of the alignment protocol is to make alignment process seamless to the higher layers of the protocol stack. Figure 1(b) shows this basic architecture which makes FSO links seem just like any other RF link to the higher layers. It is possible to let higher layers know about the dynamics of the alignment protocol to optimize communication performance for multiple transceivers of the spherical FSO nodes. However, we focus on the proof-of-concept design in Figure 1(b).

IV. Prototype

By employing commercially available off-the-shelf electronic components, we designed and built a prototype consisting of two main parts: Transceiver circuit and controller circuit. The transceiver circuit has a circular shape which includes both emitting diode and photodiode on itself, as shown in Figure 3. The controller circuit contains a microcontroller which is responsible for alignment detection, data transfer and data restoration. The controller circuit also includes the microcontroller and transistor which is responsible for driving emitting diodes at desired modulation frequency and line transceiver which is responsible to convert TTL logic levels to RS232 in order to communicate with a laptop computer.

A. Transceiver Circuit

Transceiver circuit contains 2 LEDs, one photodetector and a simple biasing circuit. Schematic of the circuit is shown in Figure 2(a) while picture of the front side and back side is shown in Figure 3. We used two LEDs are used to boost the emitted optical power and thereby effective communication range. GaA1As double heterojunktion LEDs with peak emission wavelength of 870 nm named TSFF5210 [26] is selected for transmission. TSFF5210 is a high speed infrared emitting diode which has high modulation bandwidth of 23 Mhz with extra high radiant power and radiant intensity while maintaining low forward voltage as well as being suitable for high pulse current operation. Angle of half intensity is ±10 for this LED which makes it suitable for desired node positions. The signal that is sent from microcontroller is modulated by PIC12f615 at 455 kHz and sent to LEDs. TSOP7000 series [26] is used for receiving modulated signals. TSOP7000 is a miniaturized receiver for infrared remote control and IR data transmission. PIN diode and preamplifier are assembled on lead frame and the epoxy package is designed as IR filter. The demodulated signal can directly be decoded by a microcontroller. The circuit of the TSOP7000 is designed so that disturbance signals are identified and unwanted output pulses due to noise or disturbances are avoided. A bandpass filter, an automatic gain control and an integrator stage is used to suppress such disturbances. The distinguishing marks between data signal and disturbance are carrier frequency, burst length and the envelope duty cycle. The data signal should fulfill the following conditions:

- The carrier frequency should be close to 455 kHz.
- The burst length should be at least $22\mu s$ (10 cycles of the carrier signal) and shorter than $500\mu s$.
- The separation time between two consecutive bursts should be at least $26\mu s$.
- If the data bursts are longer than $500\mu s$ then the envelope duty cycle is limited to 25% .
- The duty cycle of the carrier signal (455 kHz) may be between 50% ($1.1\mu s$ pulses) and 10% ($0.2\mu s$ pulses). The lower duty cycle may help to save battery power.

TSOP7000 can communicate up to 19200 bit/s and this is the bottleneck for the prototype's data rate. We used serial communication to transmit data between nodes and serial communication can communicate up to 460800 bit/s. Different types of photo-detectors can be used to increase data bandwidth.

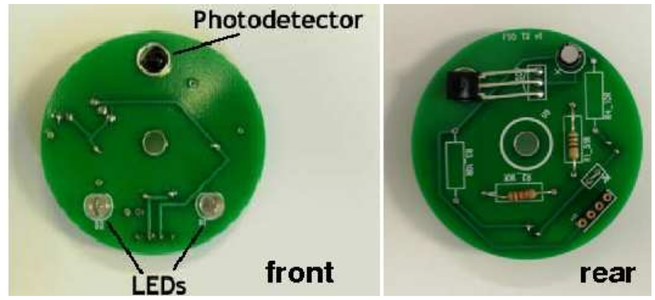


Fig. 3. Transceiver circuit front and rear view.

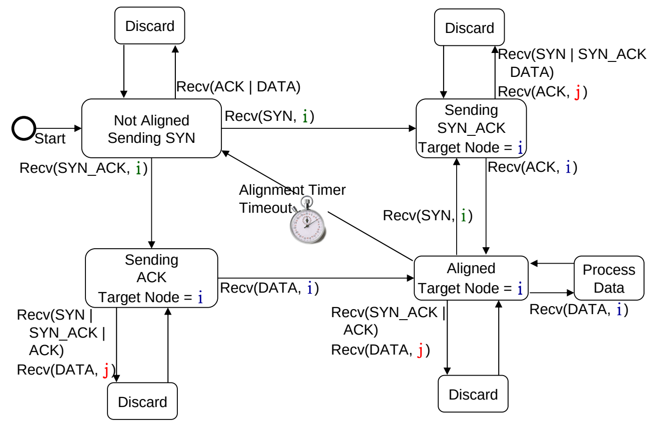


Fig. 4. State diagram of alignment algorithm.

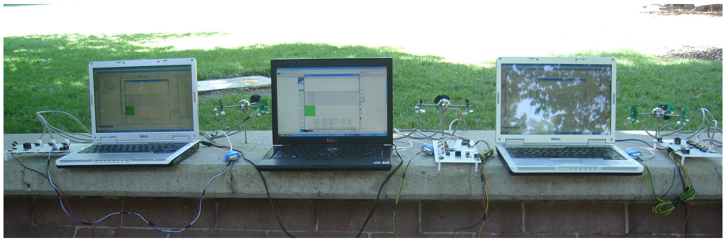
B. Controller Circuit

Transmission units, data sent and received via transceivers that are controlled by a microcontroller. Microcontroller handles all the alignment protocol in itself and decides whether and alignment is established or not. It also detects if the alignments goes down and buffers data that will be sent upon re-establishment of the alignment. We used PIC24FJ128GA106 a 16 bit microcontroller [27] for implementing the alignment algorithm. Controller circuit as shown in Figure 2 is responsible for searching alignment and data transmission continuity via transceivers simultaneously.

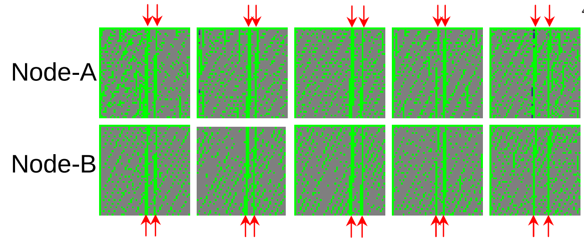
Because each prototype FSO structure has 3 transceivers connected to it and we use RS-232 communication there must be 4 serial port on the microcontroller. Software serial ports can be implemented on a microcontroller's digital input and output pins as the number of digital pin count lets, but this will be without an internal buffer on digital input and output pins. Our alignment and data transmission algorithm needs buffering when the frames received and transmitted, and thus, microcontroller must have built-in serial ports. PIC24FJ128GA106 carries 4 built-in bidirectional serial ports onboard.

C. Alignment Protocol

The essence of our LOS alignment protocol is to exchange small frames between neighbor multi-element FSO nodes and identify the transceivers that are in line-of-sight of each other. The protocol aims to establish a *bi-directional* optical wireless



(a) Experiment setup: 3 laptops (collinear placement), each with a 3-transceiver optical antenna.



(b) Throughput screen shots of a prototype experiment where transmitting node is mobile.

Fig. 5. Experiment setup with 3 nodes and screen shots showing throughput results for 5 iterations. Second figure shows straight green lines in which the transmitting node gains mobility. Red arrows indicate loss of alignment (and data) due to mobility. Once the mobile node returns to its place, data phase is restored and transmission continues. (Green spots show data loss)

link and hence uses a simple three-way handshake messaging method for full assurance of the alignment (Figure 4). Our alignment protocol uses a small frame (e.g., 4 bytes long), hence a frame does not keep the physical channel busy for too long. A frame starts with a FRAME_START byte, indicating the start of channel usage by another transceiver. SENDER_ID and RECEIVER_ID fields follow the frame indicator. Both bytes are node IDs instead of transceiver IDs. Last byte is the FRAME_TYPE byte that indicates the intention of the sender of this frame. In a frame of type DATA, the fifth byte is the length of the payload. Hence, the payload is variable-length.

There are 4 different types of frames. SYN, SYN_ACK, ACK and DATA. Re-alignment algorithm starts by sending SYN frames through a particular transceiver (lets assume A.1 on node A). The algorithm keeps sending this initial signal periodically until it receives a SYN_ACK answer to its SYN or it receives a SYN originated from a transceiver on a different node than itself (B.1 on node B). If it receives a SYN, it replies with a SYN_ACK. If it receives a SYN_ACK, it replies with an ACK. For simplicity, let's follow the case in which that A.1 sends a SYN, B.1 replies with SYN_ACK and A.1 replies with an ACK. When A.1 sends out its first ACK frame it changes internal state to ALIGNED with node B and same is true for B when it receives the ACK. At this point, B and A starts exchanging DATA frames. We did not implement an ACK mechanism for DATA frames to keep the protocol simple.

After a period of time (2 seconds, not necessarily idle), alignment timer goes off and changes the state of the interface to SENDING_SYN which starts the alignment process again. This simple alignment process, although exchange a very small number of frames, will disrupt the carried flow and cause drops. The algorithm has been successful in establishing the alignment at the first trial, that is with exchange of only 3 frames.

Although the alignment protocol is fairly straight forward and similar to RTS-CTS-DATA-ACK sequence found in RF MAC implementations, it plays a vital role in detection of available extra physical layer communication channels and it is the key components that makes intermittency of FSO links seamless to the upper layers as shown in Figure 1(b). By implementing a physical layer LOS alignment protocol it also becomes possible to realize solutions such as buffering of "physical layer frames" to make the FSO communication's intermittency seamless to upper layers.

V. Experiments

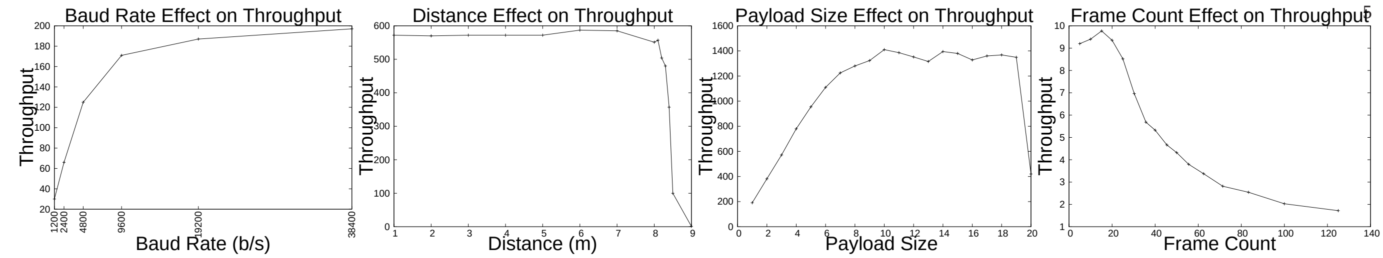
A. Proof-of-Concept Experiments

We implemented a simple FSO transceiver and alignment circuit prototype. The design consists of 3 FSO transceivers connected to a circuit board with a microcontroller. Microcontroller connects to a laptop computer (A) through RS-232 serial port. This microcontroller implements the alignment algorithm: it routinely probes for new alignments. This simple prototype is duplicated for 2 other laptop computers (B and C), so that we can establish a flow (file transfer) among the three nodes (Figure 5).

Our goal in this initial design is to test the feasibility of an LOS alignment algorithm, and demonstrate that *despite a major change in physical network topology, data phase can be effectively restored upon re-establishment of alignments*. To illustrate these goals, we present 6 experiments. Except last two experiments each experiment lasted 10 seconds and were repeated 10 times for more reliable results. In each experiment, we transfer an image file. We transfer every pixel of the file in one data frame. Hence, a typical data frame consists of 5 bytes: x and y of the pixel and red, green and blue values. First 3 experiments do not involve mobility.

1) Baud Rate Experiment: In this experiment the transmission is bi-directional. Node-A and Node-B are placed 1 meter apart from each other. The aim is to observe number of frames that can be sent per second as the baud rate varies. Here we define throughput as number of frames that can be sent in each second. We increased the baud rate from 1200 bps to 38400 bps. We observed that (Figure 6(a)) the number of frames that are successfully sent increases as the baud rate is increased. We observed that transmission becomes impossible when the baud rate goes beyond 38400 bps. Thus, 38400 bps baudrate is the upper bound for our transceivers. We used 19200 baud rate level for next experiments.

2) Payload Size Experiment: Similar to the previous experiment, Node-A and Node-B are placed 1 meter apart from each other. The transmission is again bi-directional. The aim is to observe the effect of payload size on frame count that is being sent per seconds and throughput that can be achieved. Here we



(a) Throughput behavior as baud rate varies. (b) Distance effect on throughput. (c) Payload size effect on throughput. (d) Frame count effect on channel usage.

Fig. 6. Graphs showing experiment results for various setups.

define throughput as the number of bytes that can be sent in ten seconds. We can formulate our throughput as:

$$Throughput = PayloadSize * FrameCount$$

Payload size has negative effect on frame count that frame count decreases when payload size is increased. We observed that (Figure 6(c)) we achieve maximum throughput when payload size is 15 and frame count is 93. We increased payload size until we reached maximum throughput and we observed that the negative effect of payload size increases on the frame count thus makes throughput decrease after its maximum value.

3) Frame Count Experiment: In this experiment we increased frame count that is sent in each alignment interval and observed its effects to channel usage. We can formulate our channel usage as:

$$ChannelUsage = 100 * ChannelCapacity / Throughput$$

Here the capacity is the number of frames that is sent in 10 seconds and throughput is the number of bytes thats is received in 10 seconds. We found that (Figure 6(d)) channel usage increases until it reaches its maximum value, and then decreases until channel gets its saturation due to the change on frame count that is being sent in each second. We achieved maximum channel usage of 97.68% when the number of frames that is sent is 15. The channel gets its saturation when throughput is 215 (frame in ten seconds).

4) Distance Experiment: In this experiment we observed throughput behavior as the communication distance varies. We again placed two nodes 1 meter apart from each other for the beginning condition and then increased the distance between the two nodes. We observed that throughput doesn't change until the transmission distance becomes critical for transceivers. We found that (Figure 6(b)) critical point is 8 meters. We continued increasing the distance and we found that 9 meters is the last value that transceivers can communicate with each other. Thus our critical interval is between 8th meter and 9th meter.

5) Stationary Experiments: Stationary experiment is fairly simple: Node-A sends an image file (126 by 126 pixels) to Node-B. The transmission is unidirectional. We found that since the alignment between 2 nodes is re-established every 2 seconds, nodes experience 10% data loss. This experiment reveals a simple improvement: we can delay/cancel re-alignments as long as a data flow is live and remove the 10% overhead totally.

Second experiment is done between two nodes: Node-A and Node-B. In this case, both nodes send an image file of 126x126 pixels to each other. Node-A was able receive 14136 of 15876 pixels. Node-B experienced a similar throughput: 13904 pixels.

Third experiment is conducted using 3 nodes. We placed 3 nodes in a ring topology and started file transfers from Node-A to Node-B and from Node-B to Node-C and from Node-C to Node-A. In this experiment, *every node was able to utilize its 2 out of 3 transceivers at the same time*, which clearly demonstrates the potential of spatial reuse. At the end of the transmissions, Node-A received 12950, Node-B received 9395 and Node-C received 12755 pixels.

6) Mobility Experiment: In this experiment, we placed Node-A and Node-B 2 meters apart from each other. Node-C was placed in the middle of the two. Hence, Node-C was able to connect to A and B. However, Node-A and Node-B could not connect to each other when Node C was in between. We transferred an image file of 49 by 49 pixels from Node-C to other two nodes. Transmission went on without significant disruption until the transmission reached the half of the file. We moved Node-C 1 meter away perpendicular to the line between nodes A and B, and waited for 10 seconds. 10 seconds later, we placed Node-C in its original place. Another 10 seconds later, we removed it again. And placed it back after another 10 seconds. We observed that these 10-second disruptions have a vivid effect on the file transfer and can be clearly seen on all 5 iterations of this experiment in Figure 5(b). We saw that Node-C was able to successfully restore the data transmission every time after loosing its alignments.

VI. Summary

We demonstrate a prototype of multi-transceiver spherical FSO node which can successfully hand-off multiple data flows between optoelectronic transceivers. We conclude that FSO communication systems can be embroidered with such auto-alignment mechanisms and cross-layer buffering schemes in order to overcome the inherent challenges of FSO directionality. Those mechanisms make FSO an attractive solution for the dense use cases like in a lounge as well as mobile inner-city settings.

Future work includes link layer protocol designs due to the fact that a highly intermittent connectivity pattern is presented by the proposed FSO structures when they are mobile. For the mobile cases, upper layer network protocols' performance (such as TCP) suffers from this high intermittent connectivity. Employing a link or physical layer that buffers the packets during the periods of misalignment, and provides a virtually continuous connection will be highly beneficial. We propose to use multi-channel MAC and cross-layer buffers to make the node more responsive to the alignment/misalignment events by determining those events at the MAC layer and notifying upper layers if necessary.

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