Performance Analysis of Voice Transfer Using Multi-Transceiver Optical Communication Structures

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***Abstract*—Free-space-optical (FSO) communication has recently attracted attention as a complementary alternative to radio frequency (RF) wireless networks. However, the directionality of FSO communication is prone to mobility which requires maintenance of line-of-sight (LOS) alignment between FSO transceivers. By using multiple transceivers per node and automatically detecting neighbor nodes that are in LOS each other, we showed how to maintain the LOS alignment on FSO nodes. In this paper, we present a prototype implementation of such multi-transceiver electronically-steered communication structures to measure the performance of a voice file transfer over such multi-transceiver systems. We show that by using multiple directional transceivers and LOS detection and establishment protocol, we can assign multiple logical data streams to appropriate physical transceivers and transfer different voice files simultaneously to multiple FSO nodes with tolerable disruptions and overhead.**

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

I. INTRODUCTION

Free-space-optics (FSO) communication has been used for many years in different forms such as laser communication, infrared communication, and visible light communication. Though FSO communication has been pretty successful as a point-to-point very high speed communication medium, radio frequency (RF) communication has been the primary technology used for wireless communication applications. The success of RF has been due to its advantages of handling mobility via non-line-of-sight (non-LOS) omni-directional signal propagation. Recently, FSO communication received attention because of the increasing capacity gap between RF communication (i.e., last mile) and fiber-optic communication (i.e. backbone). New technologies such as PDAs and smart-phones require more bandwidth as the Internet is growing rapidly. Approaches tackling this last mile problem are of crucial importance to the Internet's capability of penetrating and accommodating new wireless technologies at the edge.

An FSO transceiver consists of an optical transmitter (e.g., Light Emitting Diode (LED), Laser Diode and VCSELs) and receiver (e.g., Photo-Detector (PD), Photo-Transistor). Such FSO transceiver hardware has very long lifetime with low power consumption, and can be built with very low costs. Power consumption and lifetime characteristics of optoelectronic components are also attractive in comparison to RF components. Further, the form factor of the FSO devices is smaller as well. These attractive properties are accompanied by high speed communication capabilities within the optical spectrum.

FSO transmitters generate signals with optical propagation characteristics. That is, the FSO signals are highly directional and can be modulated at high speeds, e.g. 1 GHz for LEDs/VCSELs and higher for laser diodes. The directionality of the FSO signals allows spatial reuse which is not immediately available in RF signals due to their omni-directional propagation. For the same reason, FSO signals are harder to intercept and provide better security. Further, FSO concepts are applicable to large bands of unlicensed infrared or visible spectrum that is available for wavelength-division multiplexing.

To counteract these numerous advantages, FSO communication requires clear line-of-sight (LOS) and LOS alignment. It also suffers from beam spread with distance and unreliability during bad weather especially when the size of particles (e.g., aerosols and fog) in the medium is close to the wavelength used. Since FSO transmitters are highly directional, they require a mechanism or a smart algorithm to manage the LOS alignment among transceivers during an ongoing transmission. Traditionally this LOS management has been done via mechanical steering mechanisms which are expensive and requires high maintenance. Further, mechanical steering mechanisms fall short of quickly recovering from disruptions on links with a sensitive alignment or high relative mobility. Due to these difficulties, FSO has not received much attention for mobile ad-hoc communications.

In our recent work, we showed that it is possible to make FSO a mobile ad-hoc communication medium via 3-dimensional spherical "optical antennas" [1]–[4]. Once such spherical FSO structures are covered with multiple transceivers, they can achieve both (i) *angular diversity* via their spherical surface and (ii) *spatial reuse* via directionality of the optoelectronic transceivers. Instead of mechanical steering, we implement "electronic steering" over these spherical optical antennas. We employ an LOS detection and alignment establishment protocol via fast handshakes among transceivers of neighboring nodes. 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. We showed that such multi-transceiver communication structures with spherical shapes are capable of assigning logical data streams to appropriate physical transceivers/channels [4].

In this paper, we present an improved prototype with faster transceivers. We show that it is possible to make voice file transfers and evaluate performance of these transfers over our LOS detection and alignment establishment protocol. Our pro-

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totype experiment includes varying transfer speeds and codec types. For simplicity, data rate that one node can reach at each transceiver will be up to 312500 bps. It is possible to receive and process multiple voice data streams simultaneously using the directionality of FSO transceivers. With three different nodes , each node tries different voice file transfers among each other to evaluate the effects of the multi-transceiver design of the FSO structures and LOS alignment protocol on the quality of the voice by measuring the mean opinion score (MOS) of the transferred voice. We prove that disruptions below a reasonable threshold are recoverable in a seamless manner.

The rest of the paper is organized as follows: In Section II, we give the literature review for FSO transceivers and emerging FSO technologies. In the same section, we also explain our approach of multi-element FSO structures compared to previous work. In Section III, we describe our prototype including transceivers and controller boards. Section IV presents details for our experimental setup and our results. Finally, we summarize our contributions and discuss improvement areas for our work in Section V.

II. Background

There has been a large body of work on FSO communications with a focus on coding and modulation techniques to improve bit error rates achievable using an FSO link [5] [6] [7] [8] [9]. Attaining longer transmission ranges, hardware design issues, and solutions against mobility have also received significant attention. Most of these prior studies have considered single transceiver designs, with the exception of multi-transceiver designs in the area of FSO-based interconnects.

Today, most of the FSO deployments are focused on long distance (up to 7 kms) point-to-point applications with employing high-speed laser or VCSEL hardware. As an example, Canon [10] manufactures four different models of FSO transceivers capable of communicating 25 Mbps to 1.485 Gbps at 20 to 2000 meters of transmission range with a mechanical auto-tracking system which helps to manage the data transmission due to different environmental conditions such as building sway, wind, and temperature values. Another supplier MRV [11] announced the line-of-sight TereScope 10GE which is a 10 Gigabit Ethernet FSO system. MRV also has previous TS series capable of transmitting at 10 Mbps to 1.5 Gbps with up to a communication distance of 7 kms. Additionally, fSONA [12] and Lightpointe [13] announced various transceiver series that are capable of communicating at 2.5 Gbps with varying distances.

Compared with lasers or VCSELs, LEDs are modulated at lower speeds (up to 155 Mbps) but they are cheap, small, low weight. They are preferred for their low power consumption and they have longer lifetime. Most terrestrial FSO technologies (e.g., enterprise connectivity, last mile access network, and backup links) use infrared (IR) frequency band due to eye safety issues. Infrared wireless is a very simple form of FSO communication technology. Most infrared designs use LEDs as transmitters [14] [15]. Infrared FSO links can be implemented using infrared laser light, but low-data-rate communication over short distances mostly employs LEDs. LED-based systems can achieve transmission ranges as far as 3 km. However, their performance (transmission range and communication quality) is highly sensitive to atmospheric factors such as rain, fog, dust, and heat.

Success of FSO at such ultra long distances is due to the fact that FSO transmitters are highly directional and can dissipate power in a focused manner rather than omni-directional spread as in RF signals. This directionality comes with a cost of LOS alignment problem, which requires smart mechanisms to manage LOS among transceivers during an ongoing transmission. Traditionally this has been done via mechanical steering techniques which are very expensive and require high maintenance and sensitive equipment. Further, since they are essentially solutions designed for limited physical movement, mechanical steering techniques are not fast enough to recover from disruptions caused by mobility. Majority of these steering and tracking methods are focused on point-to-point applications: terrestrial last-mile, deep space [16], and building-top installations where limited spatial reuse or redundancy is achieved through one primary beam and some backup beams. Scenarios involving multi-point-to-multi-point communication are not considered by these mechanical steering approaches, since the overall optimization problem becomes much more complicated in selecting which neighbor to align with. Hence, this kind of FSO deployment is typically a mesh network installation where the tracking/steering problem is reduced to maintaining alignment with only single neighbor. Such multi-point deployments are mostly used for establishing a stationary backbone network with high throughput. So that, mobility has been impractical due to unavailability of mechanisms that achieve automatic establishment of LOS alignment among mobile neighbors.

The idea of using multiple elements/transceivers in FSO communication has been used in interconnects [17], which communicate over very short distances (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.

Voice-over-IP (VOIP) performance for wireline and local area networks has been an active research topic for many years [18]–[20]. Recently, VOIP performance over wireless networks has also become a point of interest due to increasing adoption of Wi-Fi hot spots, WiFi-enabled smart phones, and VOIP handsets [21]–[23]. As many researchers have pointed out, quality of the calls significantly drops due to CSMA (carrier-sense, multiple-access) based wireless network protocols, i.e., 802.11b, e. Due to its real time nature, VOIP needs frequent channel access and produces many relatively small packets. As increasing number of VOIP clients compete with each other for

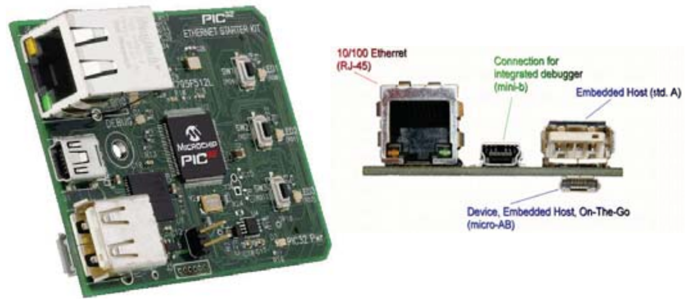

Figure 1. Picture of PIC32 Ethernet Starter Kit and starter kit connections [27]

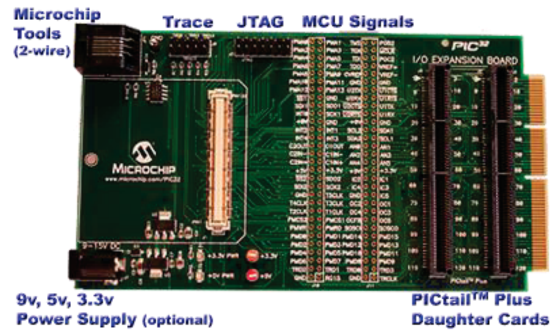

Figure 2. Picture of PIC32 Expansion Board [28]

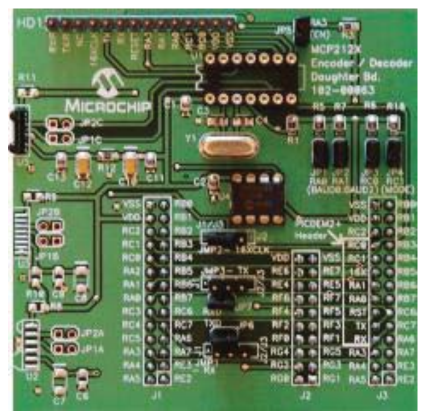

Figure 3. Picture of MCP212X Developer's Daughter Board [29]

channels of an access point, contention becomes significant. Channel access and arbitration become extremely inefficient considering the relatively small VOIP packets, frequent channel access and distorted transmission. This combination of multi-access and real-time behaviors result in poor channel utilization for the network and poor call quality for the users. Given Wi-Fi capacities and relatively modest bandwidth requirements of voice codecs deployed by popular VOIP software, this outcome can be considered surprisingly poor.

Several researchers have proposed time-division multiplexing mechanisms (TDMA) for targeting channel access contention problems by means of explicit time-slotted schemes [24]. Priority based solution mechanisms also have been proposed which emphasize fairness and voice quality [25]. In our work, we propose using FSO communication instead of popular RF-based techniques. FSO communication exploits directionality, and thus, it does not experience performance drops due to CSMA schemes required by omni-directional 802.11 protocols. Consequently, FSO is capable of providing very promising features for achieving high performance local communication services where contention due to signal interference of many densely position nodes is the norm.

III. Prototype Hardware and Design

In this section we will give information about our prototype and details of hardware we have used while building our prototype. The core concept of the prototype consists of a controller board and FSO transceivers attached to the controller board. The controller board consists of two parts, namely: (a) PIC32 Ethernet Starter Kit which is manufactured by Microchip Company [26] and provides Ethernet connectivity with TCP/IP stack software, and (b) an expansion board which allows user to fully access the MCU signals. FSO transceivers consist of an optoelectronic transmitter and receiver unit which is capable of transmitting and receiving at the same time.

Figure III shows the controller board used in our prototype. The controller board is responsible for all operations to handle logical data streams and multiple transceiver connections. The prototype uses an LOS alignment protocol [4] which exchanges small frames with neighbor multi-element FSO nodes and identifies the transceivers that are in line-of-sight of each other. The LOS alignment protocol can be also considered as an enhancement with electronic steering on top of multi-transceiver FSO communication structures. The alignment protocol uses a simple three-way handshake messaging method for full assurance of bi-directional alignment between FSO nodes. Each frame header consists of 5 bytes. The first two bytes are used for marking the beginning of a frame. The third and fourth bytes include the sender and receiver information of the neighboring FSO nodes. The last byte is intended for determining the frame type, which also provides information about current alignment status when the nodes are exchanging alignment frames. In data frames, the sixth byte represents the length of the payload. Hence, the payload length is variable. When the frame type is not data, the protocol just exchanges 5 bytes of information in order to establish the alignment. The alignment algorithm requires exchange of only 4 frames. When the frame type is data, the payload length can be up to 100 bytes.

The PIC32 Ethernet Starter kit comes with TCP/IP stack implementation and it provides Ethernet connectivity. It contains PIC32MX795F512L which is a 32bit micro-controller. The PIC32MX795F512L micro-controller has 6 UART connections, but it is possible to use only up to 3 UART connections with the kit, since the remaining connections are used for the physical peripherals of the other components on the PIC32 Ethernet

Starter Kit. The PIC32 Ethernet Starter Kit is capable of carrying out many Ethernet connectivity functions and can serve as a host computer connected to the network. The current protocols supported by TCP/IP stack are: ARP, IP, ICMP, UDP, TCP, DHCP, SNMP, HTTP, FTP and TFTP. In this prototype, we used a cross-layer design where the alignment protocol works directly with the TCP/IP stack software. Although limiting performance of our prototype, our choice of cross-layer design aims to benefit from the flexibility of working with TCP/IP protocols.

In order to access the pins of the starter kit, we used an expansion board that is developed by the Microchip Company [26]. The expansion board provides easy access to starter kit control I/O pins. Figure III shows the picture of the PIC32 Starter Kit expansion board and I/O maps of the expansion board.

One aim of the prototype is also to show that an FSO system can be built by only using off-the-shelf components. We used MCP212X Developer's Daughter Board for the transceivers. The board includes an infrared encoder/decoder and an infrared transceiver module that is capable of communicating at 312,500 bps. The transceiver module includes a PIN photodiode, an infrared emitter (IRED), and a low-power control IC. Extended IrDA provides 1 m as low power range which can be adjusted to shorter ranges via external current control resistor. The infrared encoder/decoder integrated circuit (IC) can also be used for custom designs. We used MCP2120 infrared encoder/decoder which encodes an asynchronous serial data stream, converting each data bit to infrared signal. At the receiving side, the message is encoded to UART formatted serial data.

The experimental setup consists of three laptop computers, 3 PIC32 Ethernet Starter Kits with PIC32 starter kit expansion boards, and 4 MCP212X Developer's Daughter Board. Each PIC32 Starter Kit is connected to a laptop computer via Ethernet port and the starter kit provides one host connectivity to a computer. Thus, it serves as a server to a client computer. MCP212X Developer's Daughter Boards are connected to the UART ports of the PIC32 Ethernet Starter Kits. Figure III shows the current setup. Laptop computers communicate with the starter kits using TCP connection over Ethernet, and the starter kits on each node communicate using infrared transceivers on UART ports.

IV. Experiments

We experimented with our prototype to measure the performance of a voice file transfer over a multi-transceiver FSO communication structure. The experiment setup consists of three laptop computers and three PIC32 Ethernet Starter Kits (e.g. controller boards). We connected two transceivers to laptop computer-A, one transceiver to laptop computer-B, and another transceiver to laptop computer-C, as shown in Figure III. We conducted three experiments with our prototype. First experiment measures the performance of the transceivers and second experiment measures the performance of an image file transfer which is sent from Node-A to both Node-B and Node-C at the same time. Finally, we transfer different voice files to measure the performance of voice file transfer.

Figure 4. Prototype Setup: Three nodes, Node-A sends file to both Node-B and Node-C

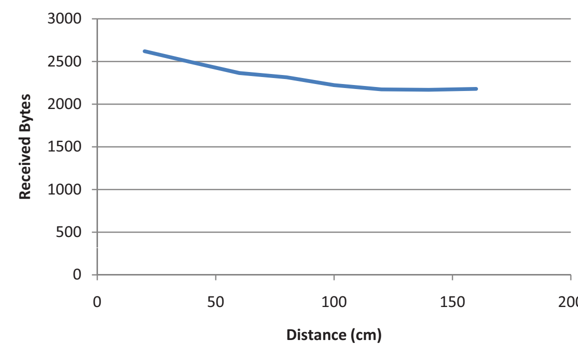

Figure 5. Transceiver performance graph: Showing the number of received bytes at varying distances

A. Transceiver Performance Test

In this experiment, we transferred a portable document file (PDF) of 3,637 bytes long from Node-A to Node-B. First, we transferred the file making a reverse connection between Starter Kit's UART transmit (TX) and receive (RX) pins by a cable connection. We transferred the whole file by success in this setup. Next, we connected the transceivers to Node-A and Node-B. The distance between Node-A's transceiver and Node-B's transceiver is set to 20 cm. Then, we increased the distance between transceivers and measured the performance of the transceivers for various distances by comparing the number of received bytes against the length of the original file. Figure 5 shows the number of received bytes depending on the distance between Node-A and Node-B. As we increase the distance between transceivers, the received byte count decreases. The operational range for the transceivers is approximately 2-3 meters.

The achieved performance by the transceivers is very low considering the performance achieved by cable connection. The main limitation is the half duplex FSO link between Node-A and Node-B. The MCP2120 cannot transmit and receive at the same time from UART port. Hence, we used two MCP2120s for each node to establish a fully functional bi-directional FSO link. The performance is significantly increased when we transferred

Figure 6. Original image and received image files for image file transfer in half duplex mode. The very left picture represents the original image file and following images are received images at Node-B and Node-C accordingly.

Figure 7. Original image file and received image files for image file transfer in full duplex mode. The very left picture represents the original image file and following images are received images at Node-B and Node-C accordingly.

the file with a bi-directional FSO link. The file is completely transferred to Node-B with a bi-directional FSO link setup.

B. Simultaneous File Transfer

We also analyzed performance of simultaneous file transfer from Node-A to both Node-B and Node-C. In this setup, laptop computer-A sends a file to both Node-B and Node-C and the performance of the file transfer is measured accordingly. We transferred an image file from Node-A to both Node-B and Node-C. The length of the image file is 7,572 bytes. When the link is in half duplex mode, the received image has been displayed in very low quality. Figure 6 shows the original image and the received image side by side for this half duplex case. When the link is in full-duplex mode, the image has been displayed in a quality closer to its original although some frames are lost. Figure 7 shows the original image and received images for the full-duplex case.

MOS	Rating	Perceived Quality
4-5	Excellent	Toll Quality
3-4	Good	Cell Phone Quality
<3	Fair	Unacceptable
<2	Bad	Unintelligible

Table I
MOS QUALITY TABLE

C. Performance of Voice File Transfer

In this experiment we transferred 6 different voice files from one node to another, where Node-A transferred a voice file to Node-B. The communication link between the two nodes is set as a bi-directional FSO link. To measure the performance of voice file transfer, we used Mean Opinion Score (MOS) which stands as an industry standard for call quality [30]. The MOS is defined on a scale of 1 to 5, and Table I shows the scale of the MOS and consequent quality perception. MOS scale is designed for rating purposes so as to allow human subjects to grade their perception of quality during a call.

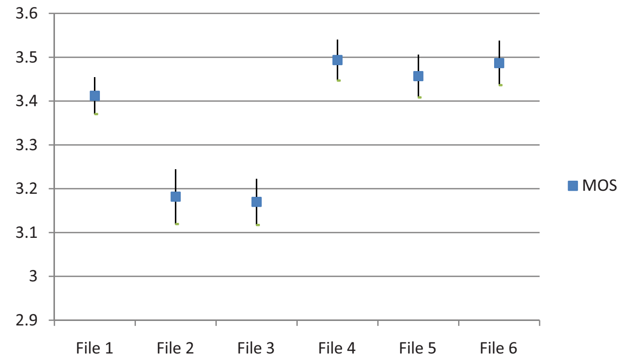

Figure 8. Voice file transfer performance graph. The MOS values are between 3 and 4 which stands as a good quality.

In our work, we have used automated methods to conduct voice quality analysis experiment instead of evaluations made by human subjects. We measured the call quality via end-to-end tests by using standard implementation provided by International Telecommunication Union (ITU) [31]. Perceptual Evaluation of Sound Quality (PESQ) is the most adopted standard for automated measurement of quality, which is calculated by comparing the voice samples received over VoIP with the original voice samples. PESQ provides a mechanism to translate voice quality into consequent MOS scores that are gathered from human judges [31]. We have used sample files given by [31] which provide various background and sampling quality challenges. For each voice file transfer, we repeated the experiments for 30 times and calculated PESQ/MOS values for each voice file. We conducted the same experiment for 6 different voice files. Figure 8 shows the average performance in terms of MOS scores for 6 different voice files within 95th percentile confidence interval. The achieved performance reflects values between 3 and 3.8 which indicates a good quality based on MOS Quality Table I.

Also, we analyzed the voice transfer performance with increasing distance between transfer nodes. As depicted in Figure 9, our prototype sustains call quality performance within close proximity, i.e., 225 cm. Beyond this diameter, call quality drops to low levels, reflecting the overall nature of FSO communications with a thresholded performance. In our work, we have used only off-the-shelf, low-cost transceivers which are limited in their transmission range. However, even with limited transmission range, by exploiting directionality, FSO communication provides high-performance local communication.

V. SUMMARY

We demonstrate a prototype of FSO system which can assign multiple data streams to the appropriate physical transceivers and transfer voice files simultaneously with minimal disruptions and overheads. The quality of the received voice is also comparable with commercial mobile phone services set by industry standards. High performance achieved by our simplistic FSO prototype, which is built on off-the-shelf products, highlights the promising capabilities of our approach that exploits direc-

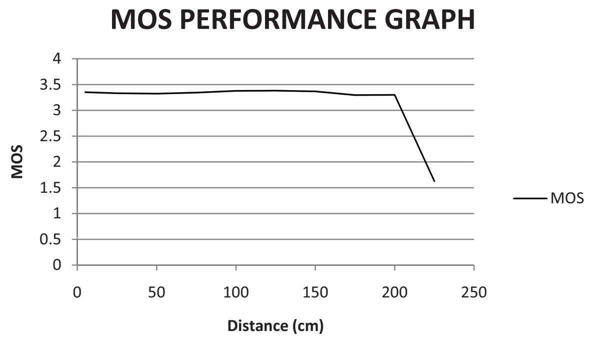

Figure 9. Voice file transfer performance graph based on varying distances

tionality for local communication. Multi-transceiver structures are capable of overcoming mobility effects on line-of-sight requirement of such directional FSO systems as we have studied earlier [4].

Future work includes the improvement on the quality of voice file transfer with different codecs and popular VOIP software. To achieve higher quality, one solution is to increase the speed of the transceivers and processing power of the controller boards. In this work, we also have not deployed any MAC level coding and modulation techniques [5]–[9] which would significantly increase data transmission capacity of our prototype. Our prototype also suffers performance drops due to lost packets while the alignment is being established between the transceivers (or in the misalignment situations). We plan to introduce link- and physical- layer buffering mechanisms that temporarily store packets during the period of misalignment. Thus, we expect that the performance of the prototype will increase when the system encounters disruptions.

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