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Automatic realignment with electronic steering of free-space-optical transceivers in MANETs: A proof-of-concept prototype

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ABSTRACT

Free-Space-Optical (FSO) communication has the potential to achieve very high wireless communication rates at tens of GHz. Although it has the advantage of high-speed optical modulation, FSO communication is prone to mobility and it requires establishment and maintenance of line-of-sight (LOS) between FSO transceivers since FSO transceivers are highly directional. We consider FSO structures with multiple transceivers placed on a spherical shape with angular diversity and tackle the problem of automatically detecting and maintaining LOS alignment among neighbor multi-transceiver FSO structures. 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 and an auto-alignment mechanism, it is possible to maintain optical wireless links in a mobile setting with minimal disruptions and overhead.

1. Introduction

Convergence of wireline and wireless multimedia applications onto the Internet has retained the demand for more bandwidth. Such streaming-style applications with heavy traffic loads and stringent service requirements present the interesting challenge of provisioning high-speed communications with fat bandwidth requirements. Internet Service Providers (ISPs) are laying fiber and will continue to do so gradually since the fiber is economically the most viable solution when evaluated based on the gained bandwidth against copper-based technologies. As a result of growing global bandwidth demand, ISPs have drastically increased their long-haul fiber network bandwidth capacities.

However, such wired optical coverage is still not able to reach as many places as the basic telephone service, because the initial cost to lay fiber optical cable is widely considered as *sunk cost*. Recent studies [2] report that only 15% of the commercial buildings in major metropolitan cities are directly connected to a fiber network. This presents a major disparity in access speeds and fiber-optic long-haul. The disparity is even more concerning when the access is limited to mobile wireless communication links. The capacity gap between radio frequency (RF) wireless and fiber-optic backbone is much larger and further increasing as backbone networks are evolving to support the huge network traffic due to the demand for high-bandwidth applications such as peer-to-peer networking, video streaming, content rich web sites, and more importantly next generation IP services such as IPTV. This large gap is likely to persist for mobile wireless links at the last mile as well since the recent growth in wireless multimedia via the use of PDAs and smart phones. The RF bandwidth is already heavily saturated and becoming more scarce as cellular capacity has mostly hit its limits. *Alternatives and solutions are urgently needed to accommodate the growth*

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in wireless demand and bridge the capacity gap between the backbone and the last-mile wireless access.

FSO communications is a promising complementary approach. It uses the unlicensed optical spectrum and most uses the same technology as the fiber optic communications. It can easily reach modulation speeds up to 10 Gbps [3]. Its propagation medium is free space and does not necessitate costly fiber cable deployments. However, it cannot penetrate through walls and needs line of sight (LOS) alignment. In order for the FSO to become a complementary communication medium for mobile wireless access, the key problem to be solved is its vulnerability against mobility [4]. The key limitation of FSO regarding *mobile* communications is the fact that *LOS alignment must be maintained* for communication to take place successfully. Since the optical beam is highly focused, it is not enough if LOS exists: The transmitter and the receiver must be aligned; and the alignment must be maintained to compensate for any sway or mobility in the nodes. Traditional solution approach to this problem of FSO communications has been to employ highly sensitive mechanical steering and tracking equipment with a powerful single transmitter such as a laser. The mechanical equipment physically rotates the transceiver to maintain the LOS alignment with the other device, which is also applying the same mechanical steering procedure. This approach can achieve establishing a wireless link even if the two communicating devices/nodes are moving with respect to each other. However, it produces device packages that are typically bulky in size, and thus, makes it very hard to develop portable FSO communication devices.

Instead of mechanical steering over powerful and expensive FSO transmitters, we propose to devise "electronic steering" over multiple cheap transceivers such as light emitting diodes (LEDs). Our recent work showed that FSO mobile ad hoc networks (FSO-MANETs) can be possible by means of such multi-transceiver devices if the transceivers are placed on a spherical surface [5–7,1]. By means of such spherical FSO devices, it becomes possible to achieve *angular diversity* via a spherical surface and *spatial reuse* via directional optical transmitters. In this paper, we present a proof-of-concept prototype of such a spherical FSO structure with multiple transceivers and evaluate 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 do not focus on designing high-speed FSO transceivers in this study, but rather focus on illustrating the feasibility of our electronic steering concept by using simple FSO transceivers composed of off-the-shelf components. Our experiment results show the feasibility of maintaining mobile optical wireless links over spherical multi-transceiver FSO structures.

The rest of the paper is organized as follows: In Section 2 we review the literature for FSO networking technologies. Then, in Section 3, we give a brief introduction about our prototype and multi-element FSO nodes. Section 4 describes our prototype in detail, including transceiver circuit, controller circuit, and alignment protocol employed to establish LOS alignment using multi-element structures. In Section 5, we present experimental results from the prototype. Finally, we discuss our conclusions and future work in Section 6.

2. Background

There has been a large body of work in FSO communications with a focus on coding and modulation techniques to improve bit error rates achievable using an FSO link [8–12]. Attaining longer transmission ranges, hardware design issues, and solutions against mobility also received significant attention. Most of these prior studies considered single transceiver designs, with the exception of multi-transceiver designs in the area of FSO-based interconnects. We cover the relevant literature on FSO hardware and mobility.

2.1. FSO hardware

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 [13] manufactures four different models of FSO transceivers capable of communicating 25 Mbps to 1.485 Gbps at 20–2000 m 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 [3] announced the line-of-sight TereScope 10 GE 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 [14] and Lightpointe [15] announced different 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, consume low power, and have longer life time. 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 [16]. Infrared FSO links can be implemented using infrared laser light, but low-data-rate communication over short distances mostly employ LEDs. Maximum range for LED-based terrestrial links is in the order of 2–3 km, but the stability and quality of the link is highly dependent on atmospheric factors such as rain, fog, dust, and heat.

FSO technology can also be successfully used in various applications which include space communications (e.g., inter-satellite and deep space) [17]. In outer space, FSO communication range is currently in the order of several thousand kilometers and it has the potential to bridge interplanetary distances of millions of kilometers using optical telescopes as beam expanders.

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 omnidirectional 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 targeted to solving 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 [18], 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 to. Hence, this kind of FSO deployment is typically a mesh network installation where the tracking/steering problem is reduced to maintaining alignment with one other neighbor. Such multi-point deployments are mostly used for establishing a stationary backbone network with high throughput and mobility has been impractical due to unavailability of mechanisms that achieve automatic establishment of LOS alignment among mobile neighbors.

This kind of last mile FSO usage 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 [19], swaying of the buildings and scintillation, using mechanical auto-tracking [20–22] or beam steering [23].

2.2. Mobile optical wireless

Mobile communication using FSO is considered for indoor environments, within a single room, using diffuse optics technology [24–31], including multi-element transmitter and receiver based antennas. Due to limited power of a single source that is being diffused to spread in all directions, these techniques are suitable for small distances (typically 10s of meters), but not suitable for longer distances.

For outdoors, *fixed* FSO communication techniques have been studied to remedy small vibrations [32,33], swaying of the buildings have been implemented using mechanical auto-tracking [34–36] or beam steering [37], and interference [38] and noise [39]. LOS scanning, tracking and alignment have also been studied for years in satellite FSO communications [40,41]. Again, these works considered long-range links, which utilize very narrow beam widths (typically in the microradian range), and which typically use slow, bulky beam-scanning devices, such as gimballed telescopes driven by servo motors.

The idea of using multiple elements/transceivers in FSO communication has been used in interconnects [42], 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.

3. Prototype implementation and experiments

In this section, we present a prototype implementation of 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. The goal of our proof-of-concept prototype is to show that by using an LOS alignment protocol over multiple directional transceivers, it is possible to maintain optical wireless communication even if two neighbor FSO structures are moving with respect to each other. We further aim to demonstrate that it is possible to establish multiple simultaneous FSO links running through different transceivers of the same FSO structure/node, which is not something possible with traditional RF-based wireless nodes due to the omni-directionality of RF signal.

Fig. 2 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. Unlike 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 handoff of data flows among different transceivers while achieving a virtually omni-directional propagation and high spatial reuse at the same time [43,6].

The main purpose of the alignment protocol is to make the alignment process seamless to the higher layers of the protocol stack. Fig. 1 shows this basic architecture which makes FSO links appear 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 spher-

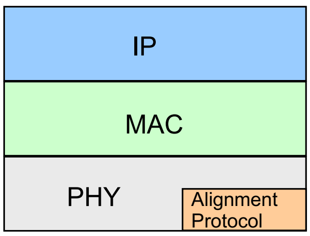

Fig. 1. Default placement of alignment protocol in protocol stack.

ical FSO nodes. However, we focus on the proof-of-concept design in Fig. 1.

4. Prototype blueprints

We designed and built a prototype consisting of two main parts by using commercially available off-the-shelf electronic components: the transceiver circuit and the controller circuit. The transceiver circuit has a circular shape which includes both emitting diode and photodiode on itself, as shown in Fig. 4. The controller circuit contains a microcontroller which is responsible for alignment detection, data transfer and data restoration. The controller circuit also includes the micro-controller and transistor which is responsible for driving emitting diodes at desired modulation frequency. A line transceiver which is responsible to convert TTL logic levels to RS232 is added to controller board in order to communicate with a laptop computer.

4.1. Transceiver circuit

The transceiver circuit contains two LEDs, one photodetector and a simple biasing circuit. The picture of the front side and back side are shown in Fig. 4. We used two LEDs to boost the emitted optical power and thereby provide an effective communication range. GaA1As double heterojunction LEDs with peak emission wavelength of 870 nm named TSFF5210 [44] were 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. The angle of half intensity is ±10 for this LED which makes it suitable for desired node positions to prove the proposed concept in prototype experiments. The signal that is sent from the micro-controller is modulated by PIC12f615 at 455 kHz and sent to the LEDs. The

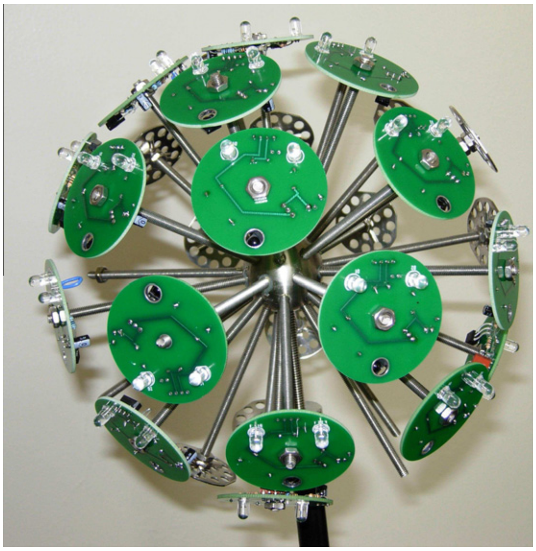

Fig. 2. Picture of prototype optical antenna.

Fig. 3. Prototype optical antenna with three transceivers.

TSOP7000 series [44] is used for receiving modulated signals. TSOP7000 is a miniaturized receiver for infrared remote controller devices and IR data transmission. A PIN diode and preamplifier are assembled on a lead frame and the epoxy package is designed as an IR filter. The demodulated signal can directly be decoded by a microcontroller. The circuit of the TSOP7000 is designed so that the 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 are used to suppress such disturbances. The distinguishing marks between the data signal and the disturbance are the 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 μs (10 cycles of the carrier signal) and shorter than 500 μs.
- The separation time between two consecutive bursts should be at least 26 μs.
- If the data bursts are longer than 500 μs then the envelope duty cycle is limited to 25%.
- The duty cycle of the carrier signal frequency of 455 kHz may be between 50% (1.1 μs pulses) and 10% (0.2 μs pulses). The lower duty cycle may help to save battery power.

These conditions are implemented using PIC12F615 series microcontroller at 455 kHz carrier frequency. The aim of this prototype is to show electronic steering mechanism and the idea of optical antennas in FSO mobile ad hoc networks which differs from point-to-point optical communication. Therefore, we implement a basic optical transceiver using TSOP7000 that can communicate up to 19,200 bits/s. We use serial communication to transmit data between nodes with speeds up to 460,800 bits/s. We do not focus on designing an high speed FSO transceiver since the focus is to show electronic steering mechanism. Different types of photo-detectors and LEDs can be used to design an high speed optical transceivers such as aforementioned devices in Section 2.1.

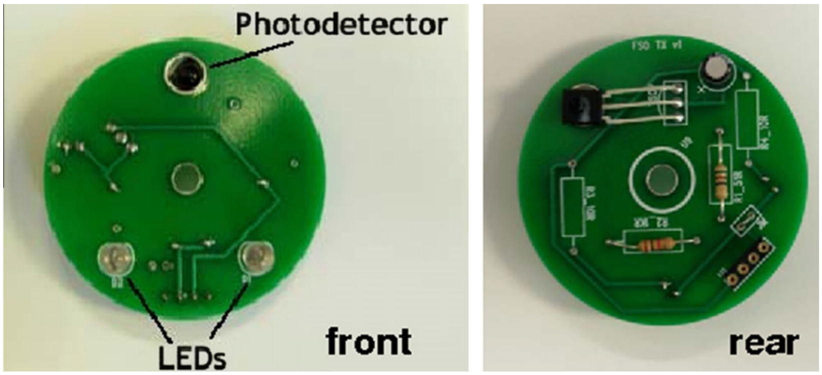

Fig. 4. Transceiver circuit front and rear views. The diameter of the transceiver board is 25 mm.

Algorithm 1. Alignment Algorithm

```
DEFINE FRAME TRANSMIT TIMER HANDLER ROUTINE:
UPON Time to transmit a frame:
for all Interfaces of the node do
  if The interface is in SENDING_SYN state then
    SEND OUT SYN FRAME
  end if
if The interface is in SENDING_SYN_ACK state then
    SEND OUT SYN_ACK FRAME
  end if
  if The interface is in SENDING_ACK state
    SEND OUT ACK FRAME
  end if
  if The interface is in ALIGNED state
    FIND a DATA Frame That Has a Next Hop That is Same With the Aligned Node
    SEND OUT DATA FRAME
  end if
end for
FRAME RECEPTION FROM A TXC HANDLER ROUTINE:
UPON The Event Of Reception of a Frame: PROCESS PROTOCOL FRAME
if Received Frame is a DATA Frame then
  RELAY Frame to Host Computer
end if
FRAME RECEPTION FROM HOST COMPUTER HANDLER ROUTINE:
UPON The Event Of Reception of a Frame:
BUFFER Frame Temporarily
PROCESS PROTOCOL FRAME ROUTINE:
UPON The Event Of Reception of a Frame:
if The interface is in SENDING_SYN state then
  if Received Frame is a SYN Frame then
    UPDATE State as SENDING_SYN_ACK
  end if
  if Received Frame is a SYN_ACK Frame then
    UPDATE State as SENDING_ACK
  end if
end if
if The interface is in SENDING_SYN_ACK state
  if Received Frame is a SYN_ACK Frame AND Received From the Same Node then
```

Algorithm 2. Alignment Algorithm (cnt.)

```
  end if
  UPDATE State as SENDING_ACK
  if Received Frame is a ACK Frame AND Received From the Same Node then
    UPDATE State as SENDING_DATA
  end if end if
if The interface is in SENDING_ACK state then
  if Received Frame is a SYN_ACK Frame AND Received From the Same Node then
    UPDATE State as SENDING _DATA
  end if
  if Received Frame is a DATA Frame AND Received From the Same Node then
    UPDATE State as SENDING_DATA
  end if
  if Received Frame is a SYN Frame then
    UPDATE State as SENDING_SYN_ACK
  end if
end if
if The interface is in SENDING_DATA state then
  if Received Frame is a SYN Frame then
    UPDATE State as SENDING_SYN_ACK
  end if
end if
```

4.2. Controller circuit

Transmission units that carry the sent and received data are controlled by a micro-controller that runs the alignment protocol to decide whether an alignment is established or not. It also detects if an alignment goes down and it buffers data until the alignment is re-established. We used the 16 bit microcontroller *PIC*24*FJ*128*GA*106 [45] for implementing the alignment algorithm. The controller circuit shown in Fig. 5 is responsible for searching for possible alignments and simultaneous data transmission through multiple transceivers.

Because each prototype FSO structure has three transceivers connected to it and we use RS-232 communication, there must be four serial ports on the microcontroller. Software serial ports can be implemented on

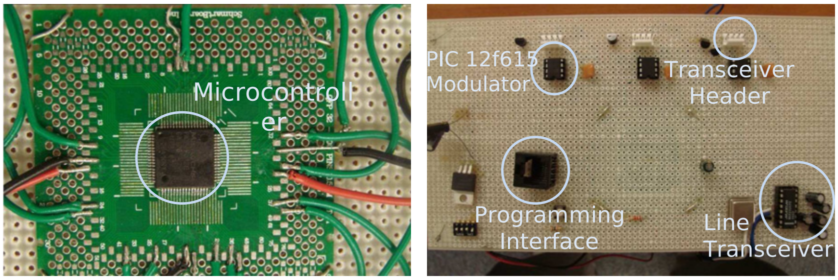

Fig. 5. Controller circuit front and rear view.

a micro-controller's digital input and output pins. However, this approach lacks internal buffers on digital input and output pins. Our alignment and data transmission algorithm needs buffering when the frames are received and transmitted and requires a micro-controller with built-in serial ports. The PIC24FJ128GA106 carries four built-in bidirectional serial ports onboard.

4.3. Alignment protocol

The essence of our LOS alignment protocol is to exchange small frames between neighboring FSO nodes and identify the transceivers that are in each other's line-of-sight. The protocol aims to establish a *bi-directional* optical wireless link and hence, it uses a simple three-way handshake method for full assurance of the alignment (Fig. 6). Our alignment protocol uses a small control frames of 4 bytes. 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 length is variable.

There are four different types of frames: SYN, SYN_ACK, ACK and DATA. The 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 us 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 its 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 2 s, the 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 exchanges 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 three frames.

Although the alignment protocol is fairly straightforward and similar to the RTS-CTS-DATA-ACK sequence found in RF MAC implementations, it plays a vital role in detecting available extra physical layer communication channels and it is the key component that makes intermittency of FSO links seamless to the upper layers as shown in Fig. 1. 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.

4.4. Handling optical feedback

Most of the infrared transceivers operate in half duplex mode because the receiver of a transceiver gets blind by its own signal when it is transmitting. This limitation is known as optical feedback. Our transceivers has a circular shape (Fig. 4) and the diameter of a transceiver board is 2.5 cm. We placed the infrared photo-detector (PD) TSOP 7000 at the back of the transceiver boards in order to reduce the effect of the optical feedback. However, we still experienced optical feedback although we covered PDs (TSOP 7000) with different materials such as aluminum foil, plastic tape, or filters. Elimination of the feedback can effectively double the transmission capacity, since it would be possible to operate in full-duplex mode.

The optical feedback is a major issue for FSO transceiver design since a node may be confused by its own transmitted signal when it is trying to find the possible alignments via its transceivers. Thus, the alignment algorithm may not work properly if a node can receive its own signal. This problem can be solved by adding more on-board hardware to the transceivers or by designing the software running on the micro-controller so that the transceiver operates in half-duplex mode. We followed the latter approach for our proof-of-concept prototype and left the implementation of a full-duplex transceiver for future work. As we mentioned previously, alignment algorithm starts by sending SYN frames and a frame starts with a FRAME_START byte followed by SENDER_ID and RECEIVER_ID. We simply ignored all the frames at the receiver side if SENDER_ID is the node itself. Furthermore, micro-controller checks every received signal and fetches the self frames by detecting

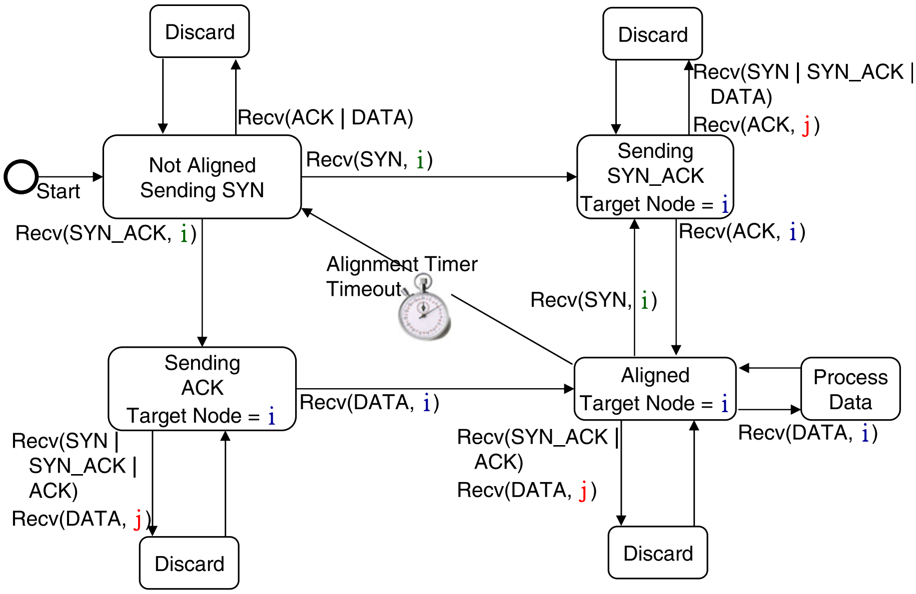

Fig. 6. State diagram of alignment algorithm.

node's SENDER_ID and ignores them. This implementation essentially employs a software filter which works properly and prevents the alignment algorithm from malfunctioning.

5. Experiments

5.1. Proof-of-concept experiments

We implemented a simple FSO transceiver and alignment circuit prototype. The design consists of three FSO transceivers connected to a circuit board with a micro-controller (Figs. 3 and 5). The micro-controller connects to a laptop computer (A) through RS-232 serial port. This micro-controller implements the alignment algorithm: it routinely probes for new alignments. This simple prototype is duplicated for two other laptop computers labeled B and C, so that we can establish file transfers among the three nodes (Fig. 7).

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 six experiments. Each experiment lasted 10 s and was repeated 10 times for more reliable results except for the last two experiments. 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. The first three experiments do not involve mobility.

5.1.1. Baud rate experiment

The transmission is bi-directional in this experiment. Node-A and Node-B are placed 1 m apart. Our aim is to observe the number of frames that can be sent per second as the baud rate varies. Here we define throughput as the number of frames that can be sent in each second. We increased the baud rate from 1200 bits/s to 38,400 bits/s. As shown in Fig. 10, we observed that 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 38,400 bits/s. Thus, 38,400 bits/s baud rate is the upper bound for our transceivers. We used 19,200 baud rate level for the remaining experiments.

5.1.2. Payload size experiment

Similar to the previous experiment, Node-A and Node-B are placed 1 m apart. 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 achievable throughput. Here we define throughput as the number of bytes that can be sent in 10 s. We can formulate our throughput as:

$$Throughput = Payload\ Size * Frame\ Count$$

Payload size has a negative effect on frame count since frame count decreases when payload size is increased. Fig. 12 shows that we achieve maximum throughput when payload size is 15 and frame count is 93. We increased payload size until we reached the maximum throughput. We observed that the increased payload size has a negative effect on the frame count and it makes throughput decrease beyond a certain maximum value.

5.1.3. Frame count experiment

In this experiment, we increased frame count that is sent in each alignment interval and observed its effects on channel usage. We can formulate our channel usage as:

$$Channel\ Usage = 100 * Channel\ Capacity/Throughput$$

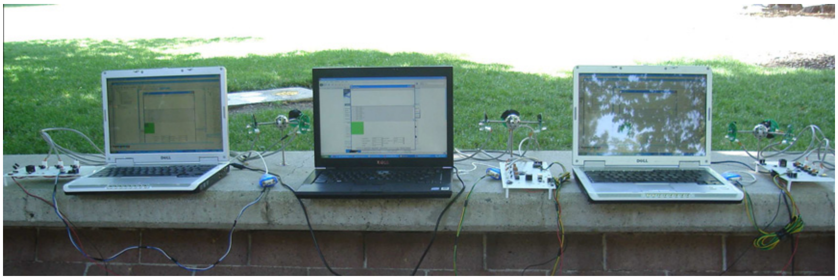

Fig. 7. Experiment setup: three laptops (collinear placement), each with a 3-transceiver optical antenna.

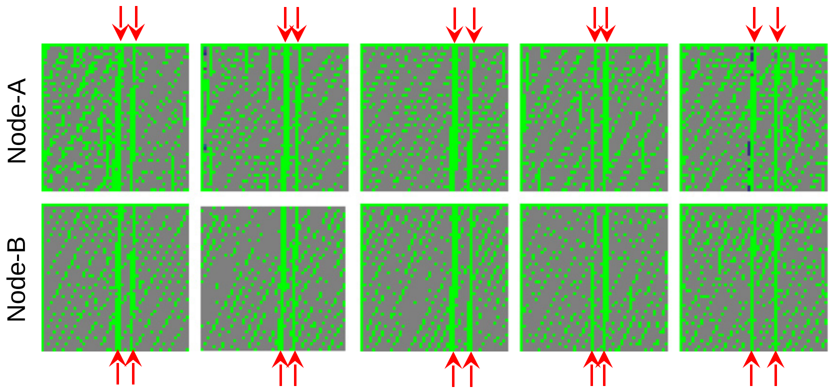

Fig. 8. Throughput screen shots of a prototype experiment where transmitting node is mobile. Straight green lines show the drops due to the transmitting node's mobility. Red arrows indicate loss of alignment (and data) due to mobility. Once the mobile node returns to its place, data phase is restored and transmission continues (green spots show data loss). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

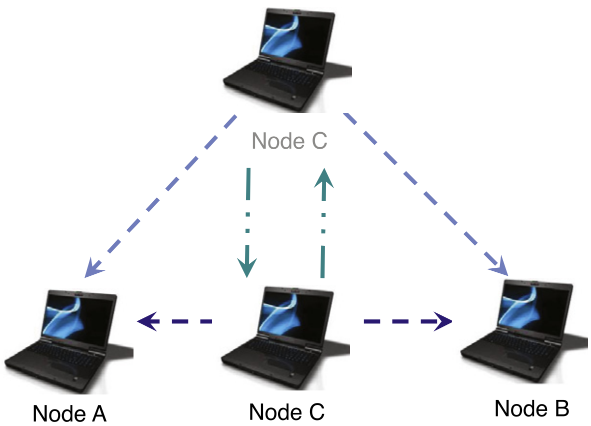

Fig. 9. Experiment setup: three laptops (collinear placement), Node-C is moving backward and then forward.

Here the capacity is the number of frames that is sent in 10 s and throughput is the number of bytes that is received in 10 s. We found that (Fig. 11) channel usage increases until it reaches its maximum value, and then decreases until channel saturates due to the change in frame count that is being sent in each second. We achieved the maximum channel usage of 97.68% when the number of frames being sent was 15. The channel saturates when throughput is 215 frames in 10 s.

5.1.4. Distance experiment

In this experiment, we observed throughput behavior as the communication distance varies. We, again, placed two nodes 1 m apart for the initial condition and then increased the distance between the two nodes. We observed that throughput does not change until the transmission distance becomes critical for transceivers. As shown in Fig. 13, we found that the critical point is 8 m. We continued increasing the distance and we found that 9 m is the maximum separation for transceivers to communicate. Thus, our critical interval is between 8 and 9 m.

5.1.5. Stationary experiments

The 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 two nodes is re-established every 2 s, the nodes experience 10% data loss. This experiment reveals a simple improvement: we can delay/cancel re-alignments as long as a data flow is alive and totally remove the 10% overhead.

In the second experiment, both nodes send an image file of 126 $\times$ 126 pixels to each other. Node-A was able to receive 14,136 of 15,876 pixels. Node-B experienced a similar throughput of 13,904 pixels.

The third experiment is conducted using three nodes. We placed three nodes in a ring topology and started file transfers from Node-A to Node-B and from Node-B to

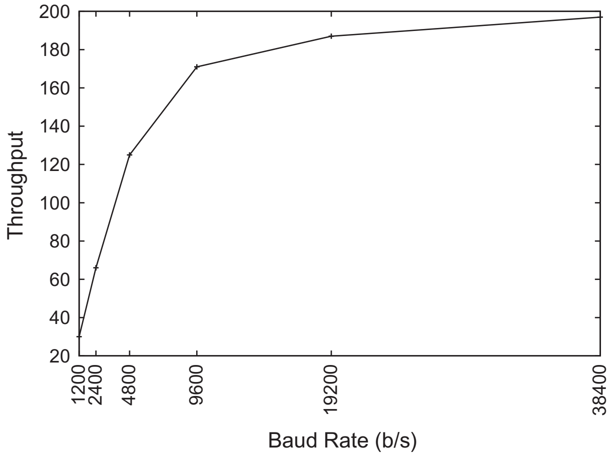

Fig. 10. Throughput behavior as baud rate varies.

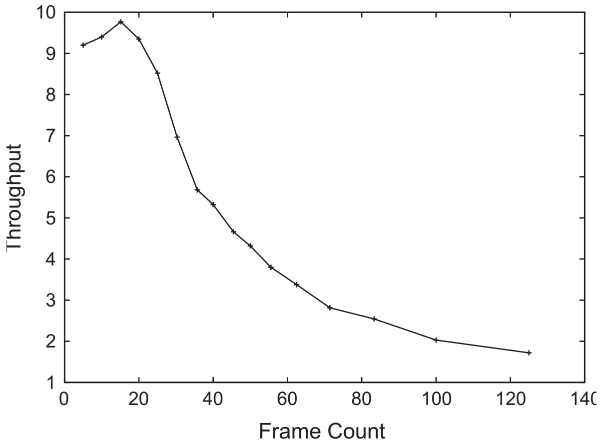

Fig. 11. Frame count effect on channel usage.

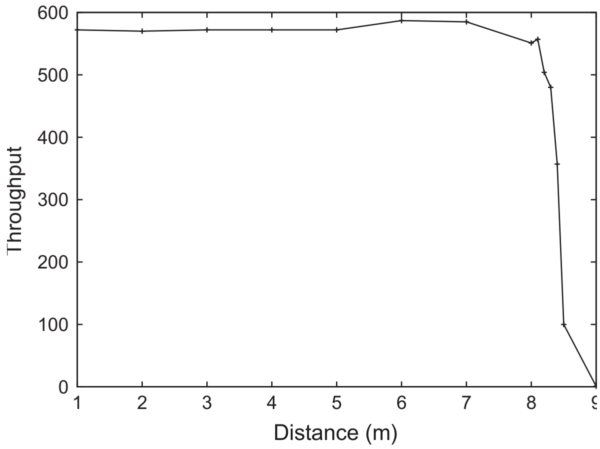

Fig. 13. Distance effect on throughput.

Node-C and from Node-C to Node-A. In this experiment, *every node was able to utilize 2 out of its 3 transceivers at the same time*, which clearly demonstrates the potential of spatial reuse. At the end of the transmissions, Node-A re-

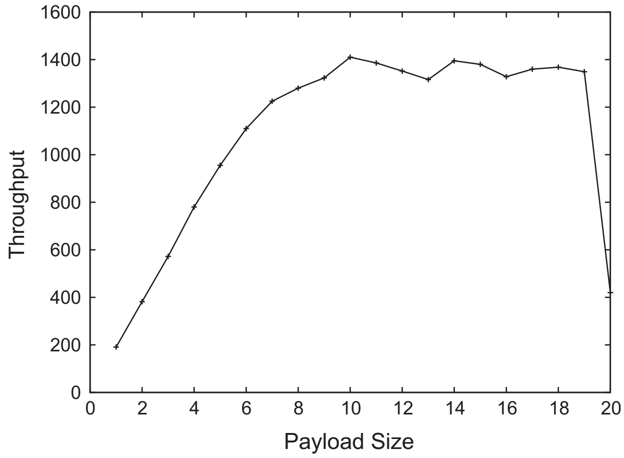

Fig. 12. Payload size effect on throughput.

ceived 12,950 pixels, Node-B received 9395 pixels and Node-C received 12,755 pixels.

5.1.6. Mobility experiment

In this experiment, we placed Node-A and Node-B 2 m apart while Node-C was placed midway between them. Hence, Node-C was able to connect to A and B. While, Node-A and Node-B could not communicate when Node C was in between. We transferred an image file of 49 by 49 pixels from Node-C to the other two nodes. The transmission went on without significant disruption until the transmission reached the half of the file. We moved Node-C 1 m away perpendicular to the line between Nodes A and B, and waited for 10 s (Fig. 9). Ten seconds later, we placed Node-C in its original location. Another 10 s later, we removed it again, then returned it after another 10 s. We observed that these 10-s disruptions have a marked effect on the file transfer as can be clearly seen on all five iterations of this experiment in Fig. 8. We saw that Node-C was able to successfully restore the data transmission every time after loosing its alignments.

6. Summary and future work

We demonstrated a prototype of a multi-transceiver spherical FSO node which can successfully hand off multiple data flows among FSO transceivers. Simply, Off-the-shelf components are used to implement the concept of spherical FSO nodes. We employed micro-controllers to implement a line-of-sight (LOS) alignment protocol which automatically hands off logical data flows among the physical FSO transceivers. Infrared LEDs and photo-detector pairs are used as the FSO transceivers and we showed several experiments using three laptops each with a three-transceiver circular FSO unit. We conclude that an FSO communication system can be embroidered with such auto-alignment mechanisms 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. Our electronic steering mechanism makes FSO technology applicable to mobile communications.

The approach of FSO communication via multi-element antennas has also an attractive potential towards being used as the next generation wireless communication technology because of its high-speed modulation capability compared to RF. FSO antennas have less power consumption while omni-directional antennas need more power to send the signal in all directions. We plan to add more transceivers on our prototype and increase the number of nodes beyond three in our FSO-based MANET. We also plan to increase the data rate of the prototype and make it especially closer to the Ethernet speeds to bring the desired impact in wireless networks.

Acknowledgments

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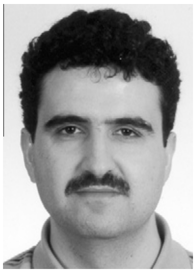

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