Electronically Steerable Mobile Optical-Wireless Mesh-Network

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***Abstract*—Free Space Optical (FSO) Communication provides better communication coverage and higher data rate. However, FSO requires neighboring nodes to schedule their transceiver towards each other for communication, which makes multi-hop communication challenging. In this paper, we present an FSO mesh network system that enables data transfer among multiple nodes. Each node is equipped with a multi-transceiver FSO communication module and a low-bitrate long-range (LoRa) omnidirectional radio frequency (RF) communication module. Scheduling remains a significant challenge for wireless communication using highly directional transceivers such as FSO. Hence, we propose a distributed coordination and communication method that utilizes a supplementary omnidirectional LoRa channel for distributed coordination among the nodes in the mesh network. In the proposed scheme, a per-packet beam scheduling is proposed where the assisting low bandwidth omni-directional channel helps the higher data rate directional channel to coordinate and face the line of sight. Our proposed method enables communication via both single-hop and multi-hop FSO links. We also present the implementation of a proof-of-concept prototype of an RF-FSO communication module comprising multiple FSO transceivers and a LoRa transceiver using commercial off-the-shelf devices (COTS). We demonstrate the effectiveness of our proposed FSO mesh network system through real test-bed experiments using the developed prototype.**

***Index Terms*—FSO, Directional, LoRa, Distributed coordination, Side channel**

I. INTRODUCTION

Wireless mesh networks (WMNs) is a significant part of the solution for the broadband wireless Internet. It provides seamless data connectivity for both indoor and outdoor environments without the use of enormous amounts of wired communication equipment [1], [2]. WMNs facilitate the progressive transmission of information in multi-node networks. The high throughput demand for providing backhaul connections in wireless networks has led to widespread interest in high speed directional communication systems utilizing FSO transceivers [3]–[5]. Unlike the traditional omnidirectional RF transceivers which are prone to unwanted interference, jamming, or interception, highly directional transceivers provide are less vulnerable to eavesdropping, provide enhanced signal security, and has lower probability of interference [2]. FSO transceivers have longer communication range and can enable multi-Gbps data transfer rates. Design and implementation of multi-transceiver modules using FSO transceivers can also help establish multiple parallel wireless communication links through spatial reuse [6].

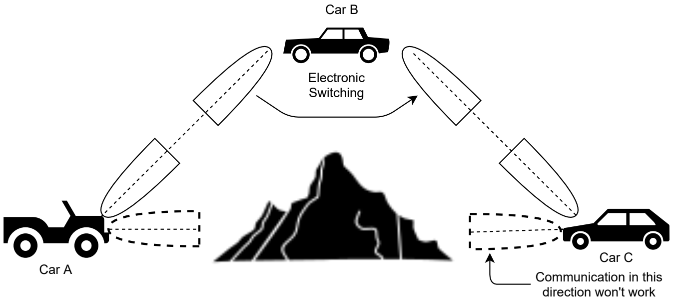

Fig. 1: Mesh network using directional transceivers using electronic beam steering. Here, B needs to switch to the appropriate transceiver in line of sight with the target neighbors A and C.

Due to high directionality, FSO communication requires maintenance of line-of-sight (LOS) among the neighbor nodes. The transceivers of two nodes must be facing towards each other for successful communication. The nodes in the FSO mesh network establishes LOS communication links using the method proposed in our earlier work in. As shown in Fig. 1, nodes without direct LOS FSO link between each other (e.g., Car A and Car C) requires the help of one or more intermediate nodes (e.g., Car B) to bridge the gap. Here, Car B has LOS links established with both Car A and Car C.

In [7], the authors found out that their designed directional MAC protocol outperforms IEEE 802.11 in terms of throughput and end-to-end delay. This reveals the prime benefits of deploying directional antennas in wireless ad hoc networks. In order to achieve omnidirectional data transmission, a single node needs to deploy multiple directional antennas [8]. Earlier, researchers mainly focused on two kinds of neighbor discovery algorithms: 1)deterministic neighbor discovery and 2) probabilistic algorithms. In deterministic neighbor discovery, a predefined sequence is provided, which guarantees neighbor discovery within a guaranteed time [9]. The deterministic algorithms usually require more time to discover the line of sight (LOS) between two neighboring nodes. On the other hand, many probabilistic algorithms are proposed where two neighbors randomly orient their beams for a handshake, which requires less time on average but can not guarantee neighbor discovery within a fixed time [10].

In this paper, we present an FSO mesh network system where multiple nodes can establish communication links with each of its neighbors. Two nodes within each other's communication range with direct LOS can establish single-hop FSO links. On the other hand, if there are obstacles hindering LOS between the nodes, multi-hop FSO links are established. For coordinating the communication with multiple nodes using separate LOS links, our proposed system utilizes a supplementary omnidirectioanl LoRa channel. The FSO links are dedicated to transferring payload. To en able communication with multiple nodes, we have developed a module comprising multiple optical transceivers and one LoRa transceiver. Each node is equipped with such a module and can electronically steer it FSO beam by electronically switching from one transceiver to another to cover the surrounding 360° space. We provide the major contributions of the paper below.

- We propose a distributed coordination protocol for communication with multiple nodes simultaneously.
- We propose the use of a supplementary omnidirectional LoRa channel for the coordination.
- The design of a multi-FSO-transceiver module with electronic beam steering capability.
- A communication method through multi-hop LOS FSO links.
- Prototype implementation of the communication module using an omnidirectional LoRa [11] transceiver and multiple IrDA3 Click [12] transceivers.
- Through real-testbed experiments, we present the effectiveness of our proposed multi-hop FSO mesh network.

The rest of the paper is organized as follows: In Section III, we give a comprehensive description of our prototype involving equipment and detailed device connections. We present our results in a couple of scenarios and discuss our conclusions in Section IV and Section V, respectively.

II. MULTI-HOP NETWORK

In this section, we provide the design of the proposed system. First, we present the system assumptions and preliminaries, and then we present the actual system design and algorithms.

A. System Assumptions

Figures 2 and 3 show the general concept of a circular FSO node with multiple transceivers. Our design is based on the two principles of the directional transceiver,

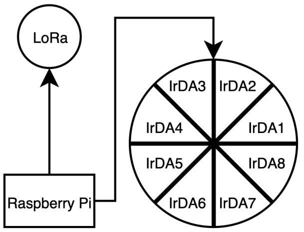

Fig. 2: Node Block Diagram

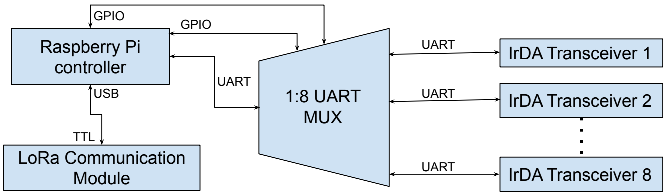

Fig. 3: Eight Transceivers Node Circuitry

- **Multiple transceivers:** All the nodes are equipped with multiple directional transceivers that can cover the whole horizontal plane, as can be seen in Figure 2. In this scenario, multiple communications can occur on the same frequency parallelly as long as the directional communication transceivers are not interfering with each other. This increases the spatial reuse of the communication channel.
- **Electronic beam switching:** The transceivers are controlled by a central controller, and at one point in time, only one transceiver could be selected for communication. As can be seen in Figure 3, eight IRDA transceivers are connected to the main controller, a Raspberry Pi, through a 1:8 Multiplexer. The computer can steer the beam electronically by changing the selector line of the multiplexer. The electronic beam switching is faster compared to the mechanical rotation of the transceiver head.
- **Assisting Omni channel:** The nodes are equipped with a low bit rate long-range omnidirectional communication transceiver for distributed coordination of the directional transceivers.
- **Multi-Hop communication:** It also allows multi-hop communication where data can be relayed over multiple intermediate nodes.

B. Need for communication protocol

Since the nodes use multiple directional transceivers for data communication and at one time only one transceiver could be used for data communication, two nodes need to select the particular transceiver that is facing each other for the data communication to take place. In a distributed system, it becomes extremely challenging without any prior knowledge. Our structure provides an electronic switching technique for a multi-element optical communication node. This structure can realize the scheduling of the transceiver's beam in a multi-hop network.

In this research, we use LoRA for coordination between neighboring nodes to initiate communication between two neighboring nodes, coordinate the time, and coordinate the selection of transceivers using electronic beam switching.

C. Data communication protocol

Our data communication protocol can be divided into two stages. The first stage is called distributed coordination. This stage is done by the *ommi-assisted communication module*. Let's say Node A is trying to communicate with Node B. For

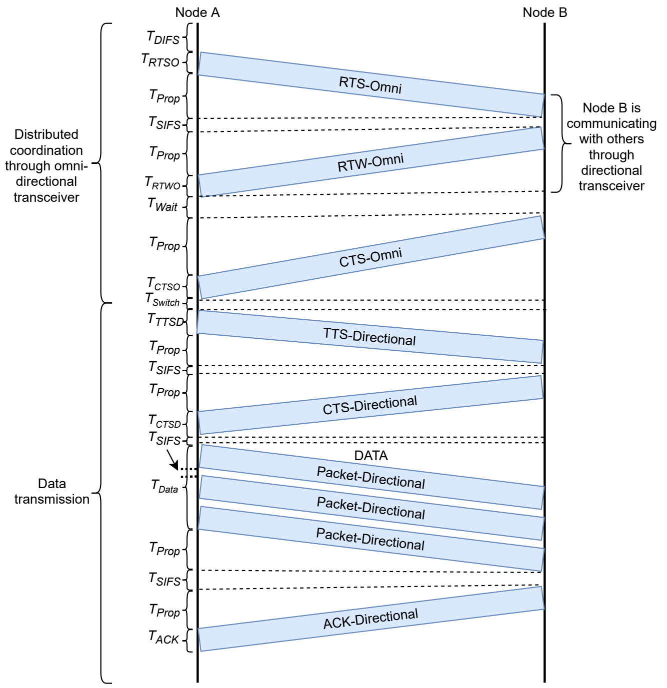

Fig. 4: Timing Diagram

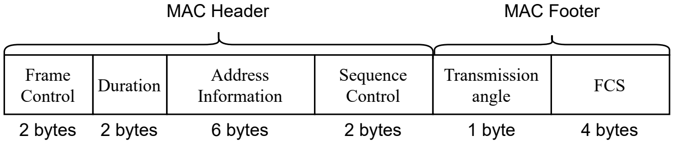

Fig. 5: Frame Format

any communication to be initialized, the transmitter node A must send a Request-to-Send frame (RTS-Omni) to its target through the omnidirectional communication module. The target, node B, will reply to the communication request from node A with a Clear-to-Send frame (CTS-Omni) through the omni-assisted communication module once it has completed all its work. If node B is in the process of communicating with other nodes, a Request-to-Wait (RTW-Omni) frame will be sent back to node A through the omnidirectional channel.

Abbreviation	Expansion
D_T	Packet Size
D_P	Packet Maximum Size
R_{FSO}	Data Rate of FSO Transceiver
T_{SIFS}	Short Inter-Frame Spacing
T_{DIFS}	Distributed Coordination Inter-Frame Spacing
T_{RTSO}	Request to Send through Omni-Directional Transceiver
T_{RTWO}	Request to Wait through Omni-Directional
T_{Prop}	Propagation Time
T_{Wait}	Waiting time
T_{CTSO}	Clear to Send through Omni-Directional Transceiver
T_{CTSD}	Clear to Send through Directional Transceiver
T_{Switch}	Transceiver Switching time
T_{TTSD}	Test to Send through Directional Transceiver
T_{ACK}	Acknowledgement Message
T_{Data}	DATA Transmission time

After completing the ongoing communication, Node B sends a CST signal to A. After node A receives the CTS-Omni, the data transmission channel will be tested by sending the Test-to-Send (TTS-Directional) frame from node A through its selected IrDA transceiver, which is facing node B. Successfully receiving the Clear-to-Send (CTS-Directional) frame from node B will prove that the LOS alignment has been established. Starting at this point, the data transmission from node A to node B begins. When node B accepts all the data, it will send back ACK to confirm the data acceptance, and node A will end the entire communication process. This communication process is presented in Figure 4.

Due to the compatibility with the existing MAC protocols, the header and footer of the frame are defined based on IEEE 802.11ac standards. The essential information, that is, the transmission angle utilized through the communication, takes up only 1 byte. Figure 5 depicts the frame format of our data communication protocol in detail. Given $T_{RTSO} = T_{CTSO}$ because of their identical frame length, the time delays of one complete communication in the Distributed Coordination stage can be expressed as follows:

$$T_{min}^{Omni} = T_{DIFS} + T_{SIFS} + T_{RTSO} + T_{CTSO} + 2T_{Prop}, \tag{1}$$

where, T_{DIFS} and T_{SIFS} are time delay for DCF interframe space and short interframe space in IEEE 802.11ac standard. Besides, $T_{DIFS} = T_{SIFS} + 2\tau$, where τ is the slot time. T_{Prop} refers to propagation time over the distance between the transmitter and the receiver. Note propagation delay for omni and directional antenna should be the same.

After distributed coordination, the beam of selected antennas has been electronically steered to face each other. The communication will be entering into the data transmission stage. Additional testing at the beginning of this stage is necessary to ensure that the data transfer is proceeding properly. The channel condition must be checked. The total time delay in data transmission can be given as follows:

$$T_{FSO} = T_{test} + T_{Data}, \tag{2}$$

where T_{test} is the total time delay for channel condition testing. It can be derived by:

$$T_{test} = T_{Switch} + T_{TTSD} + T_{CTSD} + T_{SIFS} + 2T_{Prop}, \tag{3}$$

where T_{Switch} is the switching time from the omnidirectional communication module to the FSO directional antenna. T_{TTSD} refers to the transmission time for a single TTS frame by using a directional antenna. T_{CTSD} refers to the transmission time for a single CTS frame. T_{Data} is the total transmission time for transmitting all data with a size of D_T. Given that the size of a packet has been limited to a maximum value of D_P, the total time T_{Data} can be obtained as follows:

$$T_{Data} = \left\lfloor \frac{D_T}{D_P} \right\rfloor \cdot T_{SIFS} + \frac{D_T}{R_{FSO}}, \tag{4}$$

where $\lfloor . \rfloor$ is a mathematical function that returns the smallest integer that is larger than the operand. R_{FSO} refers to the channel throughput. The throughput of the protocol can be obtained by:

$$Throughput = \left\lceil \frac{1}{T_{Data}} \right\rceil. \tag{5}$$

D. Multi-hop communication

A multi-hop mesh communication is governed by the upper layer routing protocol that decides which intermediary relay node to select for relaying packets. Let's consider a scenario where node A wants to send data to node B through a relay node C. In this case, Node A sends the packet to C using the protocol described above. Once the packet is received at C, it initiates a packet delivery. Joint scheduling of the packets should be an optimal choice here; however, the scheduling optimization is out of the scope of the current paper. In this design, the relay is done per packet basis.

III. PROTOTYPE

Through the use of readily available electronic components, we designed and built an 8-transceiver prototype. The prototype consists of a transceiver circuit and a microcomputer. Any neighbor discovery protocol can be run on the microcomputer to achieve alignment detection, establishment, and data transmission through UART serial communication. For the prototype, the transceiver circuit, made by multiple transceivers, MUXs, and one LoRa communication module, is directly connected to the microcomputer. The circuit is controlled by the Raspberry Pi. The microcomputer we are using is Raspberry Pi 4 Model B.

A. System Components

1) Optical Transceiver: The prototype utilizes a transceiver named IrDA 3 Click[1]. It is an Intelligent IR transceiver that is composed of two integrated circuits: 1) TFDU4101 is used for IR transmission. 2) MCP2122 is used for UART-IrDA conversion. This device can achieve a peak performance of 115.2 Kbps with the help of the on-board clock generator. Additionally, the communication range extends up to 4 meters because of the IRED (infrared emitter), the photodiode IR receiver, capacitors, and oscillators.

2) UART Multiplexer/Demultiplexer: Since there are multiple transceivers on a single node, transceiver selection is needed. A device named UART MUX[2] click is a dual, 4-Channel MUX/DEMUX for switching a single UART input to up to four outputs. The four independent UART inputs/outputs are chosen depending on the two control pins. This device can avoid signal interference by the ultra-low leakage current and low crosstalk that ensures a reliable switching operation.

3) Omnidirectional Communication Module: The omnidirectional communication module utilized in this study is E32-433T30D[3], a wireless serial port module featuring LoRa technology which could bring longer communication range and anti-interference performance. The communication distance reaches up to 8km with a maximum transmission power of only 1W. There are a total of four operating modes decided by the combination of two ports which increases the flexibility of the device.

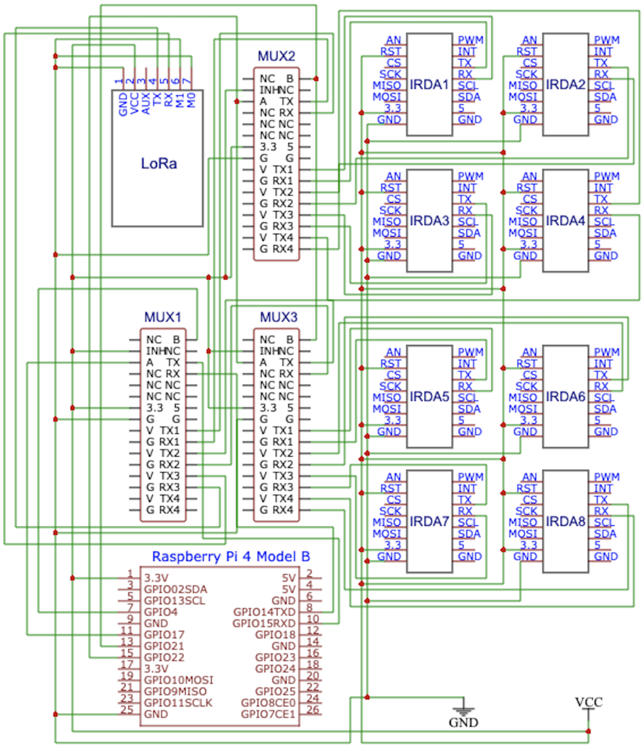

Fig. 6: Detailed circuit diagram with 8 IRDA and one Raspberry Pi as the controller.

4) Main computer: For the main computer, we used a Raspberry Pi[4].

5) Remote Control Car: The nodes are mobile. A remote-controlled (RC) high-speed car (Figure 7a and Figure 7b) are used as the nodes in this paper. The 9300 high-speed remote control car is produced by DEERC. It is a four-wheel drive, high-speed racing car with high quality and durability. It can run at a maximum speed of 40km/h. The PVC Car shell can be removed so that it is simple to customize. A two-layer structure is in place of the original shell. The Raspberry Pi and portable power supply sit on the first layer, while the transceiver circuit sits on the second layer.

B. System Circuit

To achieve a 180-degree communication range, a 4-transceiver prototype can be created. The 4-transceiver prototype consists of four IR transceivers, a UART MUX, and a microcomputer. We pasted four IR transceivers on a circular wooden board. The four IR transceivers are positioned in a semicircle and face in four different directions (45 degrees each). Since there are only four IR transceivers for this node,

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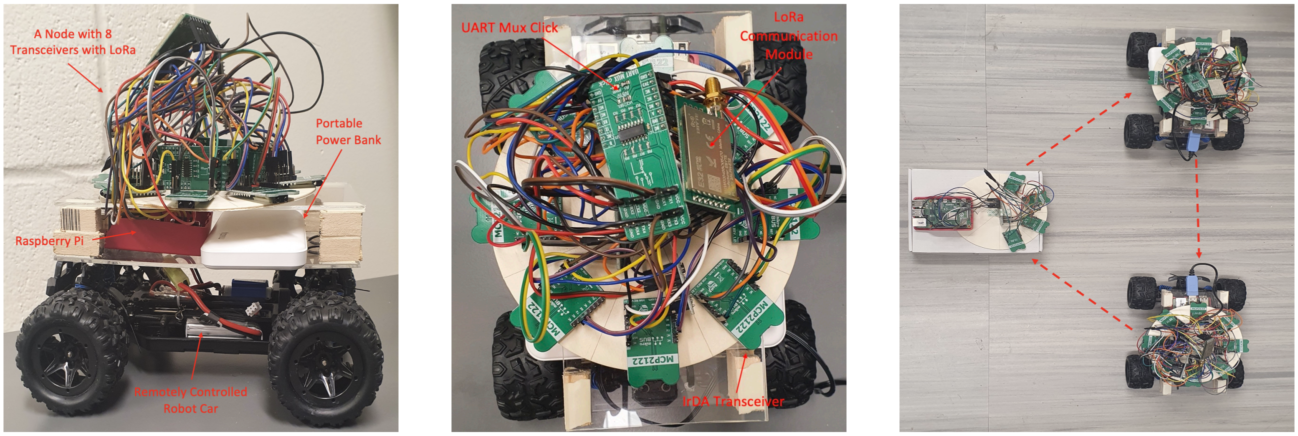
[1] www.mikroe.com/irda-3-click

[2] www.mikroe.com/mux-click

[3] olympianled.com/product/e32-433t30d-sx1278-433mhz-1w-wireless-lora-module/

[4] raspberrypi.com/products/raspberry-pi-4-model-b/



(a) Side view (b) Top view (c) Mesh network

Fig. 7: System prototype implemented on a robot cars.

only one UART MUX is used. Thereby, transceiver selection can be done by sending binary data through two GPIO ports from the microcomputer.

To achieve communication coverage in all directions, an 8-transceiver prototype is needed. The 8-transceiver prototype consists of eight transceivers, three MUXs, a LoRa communication module, and a microcomputer. Similarly, we passed eight IR transceivers on the board facing eight different directions. (45 degrees each) Unlike the 4-transceiver prototype, two additional UART MUXs are needed due to the 4-channel limit of MUXs/DEMUXs. Among the three MUXs, two of them act as followers, receiving binary data from the microcomputer to select the corresponding transceiver. The leader MUX receives another set of binary data from the microcomputer to select one of the follower MUX. Among them, two follower MUXs share the same binary data for selecting the transceiver, but only one follower MUX is selected at a time; otherwise, the LoRa communication module is selected. Therefore, only one of the eight transceivers is selected and used for data transmission. Both the MUX selection and the transceiver selection is controlled by the Raspberry Pi via a total of four GPIO ports. The complete circuit connection is shown in Figure 6, and the simplified block diagram(without three Muxs) is shown in Figure 2 and Figure 3.

IV. EVALUATION

We conducted two experiments with our proof-of-concept prototype. In the first one, we measured the throughput for direct communication between two nodes, and in the second one, we measured the throughput for two-hop communication. Both experiments are performed by using Python program programs in the raspberry PI carried by the nodes[5]. The results are also collected by the pre-written programs. For the performance test, the goal is to test the performance of the network deployed with the proposed node structure to observe the transfer rate of packets of different sizes in different network structures. For each experiment, ten packet transmissions were performed for ten packets of different sizes, from a minimum size of around 200 bytes to a maximum size of around 900 bytes. From this, we observe similar variations in data rates under different network structures.

A. One-to-One Communication

For one-to-one communication, one node serves as a transmitter, and another is a receiver. The data flow is established between them. At first, the transmitter sends out a packet, and the receiver receives it and makes a response immediately. The receiver sends what it just received to the transmitter to complete the entire communication. With this set of rules, we perform tests from using the smallest packet size to the largest packet size. The results are shown in Figure 8a. The experimental results show that the data rate increases rapidly to about 500Bps(bytes per second) with the increase of packet size in a one-to-one network. When the packet size grows to about 500 bytes, the data rate reaches its peak value and slowly decreases to 475Bps at last with the increase of packet size. IrDA transceiver has limited performance. As a result, there is a tendency to gradually rise since the IrDA transceiver can handle a small packet with ease and perform a fast enough transmission. When the size of the transmitted packet becomes larger and larger, and its physical capability is fully exploited, the data rate gradually decreases. This is expected. With all be tested, the experiment of one-to-one network indicates that the designed node can transfer an average of 490 bytes of the packet in 1.062 seconds which leads to a data rate of 439.7Bps.

B. Multi-hop Network

Multi-hop network is conducted by employing three nodes to form a network. The additional node serves as a relay. The packet is sent out from the transmitter node firstly. Then, the relay node receives the packet and sends it to the receiver node. Once the receiver receives the packet, it passes it back to the transmitter node the way the packet came. At this point, the transmission process is complete. The entire mesh network

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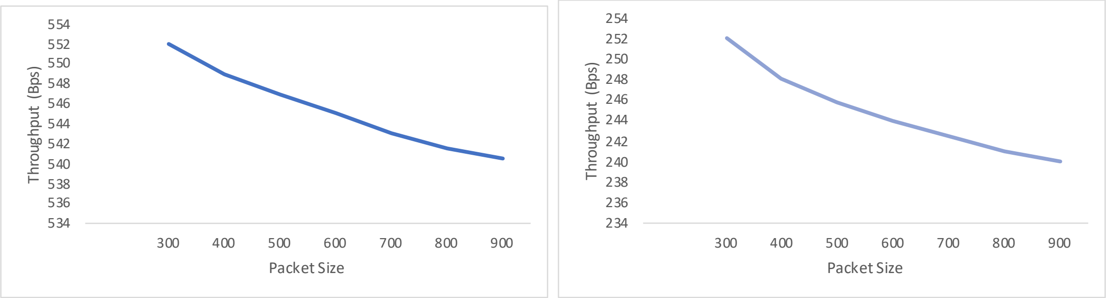
[5] The code is available at github.com/wsl-miami/nd-system



(a) Throughput for One-to-One Communication

(b) Throughput in multi-hop communication

Fig. 8: Experiment results with the prototype.

is shown in Figure 7c. It is worth mentioning that due to reflection, even if the transceiver of the receiver node is not within the communication range of the transceiver being used by the Transmitter node, the Receiver node may still get the packet sent from the Transmitter node. Therefore, we put a baffle between the two to avoid this phenomenon. Similar to a one-to-one network. We implemented the test with the same set of packets so that the difference can be observed through the method of control variates. Figure 8b shows the change in data rate with respect to the change of the packet size. From 100 bytes to 200 bytes, the data rate has a rapid growth and reaches a peak near 260Bps. Later, with the increase of packet size, the data rate declines in a slow trend. Similar to the one-to-one network, the results of the two experiments showed similar trends due to the limit of our IrDA transceiver. The experiment of a multi-hop network with three nodes reveals that our 8-transceivers node can transfer an average of 490 bytes of the packet in 2.02 seconds, which leads to a data rate of 239.5Bps.

By comparing the results of the two experiments, we observed that the node designed by us had a significantly lower data rate in the multi-hop network experiment. This is not only in the case of transferring smaller packet sizes but also in the case of transferring larger packet sizes. The data rate of the node reaches the peak when the size of the transferred packet is about 200 bytes. In addition, in the face of a large number of data transmission tasks, nodes have a relatively low data rate in the multi-hop network Scenario. It is observed that no matter how big the packet is transmitted, a multi-hop network will always consume more time to complete the transmission than a one-to-one network. For the node we designed in a multi-hop network, it takes a certain amount of time to switch to the transceiver that is used to further transmit packets according to the location of its target. In our test, the relay node needs to perform multiple transceiver switches to complete communication. As a result, the overall efficiency of multi-hop network is lower than that of one-to-one network.

V. CONCLUSION

This paper presents a design for a multi-hop wireless mesh network using directional communications. In this network, each node is equipped with multiple directional transceivers to cover all directions, and a long-range low data rate omni channel is used to assist the directional communication. In this network, two communicating nodes need to select an appropriate transceiver to communicate with each other. The nodes use a long-range (LoRa) low-bit rate omnidirectional communication channel for coordinating with each other for directional communication. After the coordination, the nodes use directional communication for a higher data rate. We implement a state-of-the-art prototype using free-space optical communication modules. The experiments show that the proposed protocol effectively enables distributed coordination in a mobile environment.

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