Neighbor Discovery in a LoRa Assisted Multi-Transceiver Free-Space-Optical Network

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***Abstract*—In this paper, we present a novel neighbor discovery method for a Free-Space-Optical (FSO) mobile ad hoc network where the nodes do not have any prior information about each other's location. Each node is equipped with multiple FSO transceivers and a low bit rate long-range (LoRa) omnidirectional communication channel aids in coordinating the neighbor discovery process to synchronize and establish directional FSO links among the nodes. Our proposed method guarantees that a node can discover all of its neighbors within one 360° FSO beam scan of the surrounding environment. We also present a preliminary prototype of an FSO transceiver module capable of electronic beam steering. Through extensive simulations and real test-bed experiments using the developed prototype, we demonstrate that the proposed method can help achieve significant reductions in discovery time compared to a state-of-the-art protocol.**

***Index Terms*—Free-Space-Optical communication, Directional Communication, Neighbor Discovery, Line-of-Sight.**

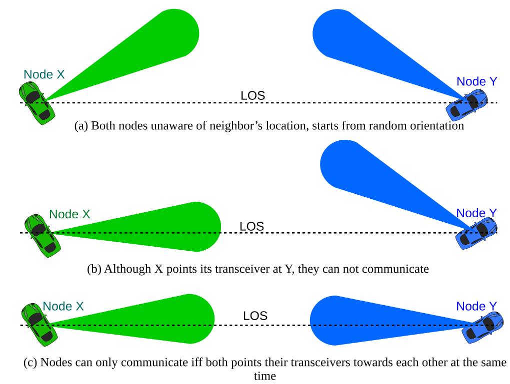


Fig. 1: Requirement of line-of-sight for neighbor discovery.

I. Introduction

In the last few decades, the demand for high speed wireless data transfer rates has grown significantly. Traditional radio frequency (RF)-based omnidirectional communication systems such as WiFi or cellular communication cannot achieve such high speed communication. In this context, directional communication such as FSO, millimeter-wave and terahertz communication have demonstrated the potential to help solve the problem of high data rate requirement [1]–[5]. FSO communication (FSOC) has gained an increase in interest due to its high-speed data transfer rate in conjunction with with its low-cost. In addition to high bit rate, FSO transceivers possess high gain properties which allow them to extend to much longer ranges compared to RF transceivers. FSOC networks are a valuable asset in military and security applications due their invulnerability to electromagnetic and radio frequency interference, making them immutable to active attackers. Furthermore, the high directionality of FSO transceivers minimizes the probability of packet collision and enhances signal security. Moreover, higher spatial reuse can help in establishing multiple parallel communication links with different neighbor nodes and thus enable much larger bandwidth compared to RF.

The coverage of directional transceivers is limited, thus their positioning is an important factor in FSO system design. As depicted in Figure 1, two FSO transceivers must establish line-of-sight (LOS)with each other for successful neighbor discovery and to begin communication. In a network where the nodes have no prior knowledge about each other's location, LOS establishment or neighbor discovery becomes more challenging. Protocols in which the nodes are oblivious to one another, meaning they have no prior knowledge of each other's location, have been explored but do not terminate in a reasonable amount of time [6]. Additionally, random based protocols do not guarantee that any neighboring node will be found [7]. To address this issue, helper initialization channels is combined with a leader election algorithm in order to guarantee neighbor discovery among many nodes. A low bandwidth omnidirectional channel, provided by LoRa [8] is used to assist nodes in coordination. In this paper, we present a novel method that ensures neighbor discovery with minimum delay. Each node is equipped with multiple highly directional FSO transceivers. Each node can electronically steer its FSO beam by electronically switching from one transceiver to another to scan the surrounding 360° space. We show that using the electronic steering capability to control the communication direction of the nodes, the problem of neighbor discovery or detection of LOS for link establishment can be dealt with effectively. We further develop a prototype and show the effectiveness through experiments.

The main contributions of this paper are listed below.

- We propose a novel neighbor discovery method for nodes with highly directional FSO transceivers.
- The proposed method guarantees neighbor discovery within one 360° beam sweep.
- The simulation results demonstrate that, for a divergence

angle of 10^o, the proposed method achieves a 99.42% and 98.19% reduction in discovery time compared to the ID based [6] and random based protocol [7], respectively. For a divergence angle of 30^o, the reduction in discovery time is 98.38% and 95.68% for ID based and random based, respectively.
- We present a proof-of-concept prototype using an omni-directional LoRa [8] transceiver and multiple IrDA3 Click [9] transceivers.

The rest of the paper is organized as follows. In Section II, we examine the prior relevant work regarding FSO and directional neighbor discovery. Details of our method and system prototype are provided in Section III. In Section IV, we present the simulation results. Section V describes the details of the system prototypes. Lastly, we conclude the paper in Section VI.

II. Related Work

Neighbor discovery for systems with highly directional transceivers have been explored recently. According to [10], although omnidirectional transceivers were thought to have faster discovery times than directional transceivers, directional antennas can result in better performance. Omnidirectional transceivers are more susceptible to packet collision and unwanted interference due to their ability to transmit and receive in all directions. On the other hand, directional transmitters are less vulnerable to interference and provides enhanced signal security and longer communication range [10].

Oblivious discovery protocols assume that the nodes in the system have no prior knowledge regarding their neighbors' location. Such asynchronous algorithms based on unique identification (ID) numbers have been proposed in [6], [11], [12] for nodes with mmWave transceivers. Although these methods ensure discovery within a bounded time period, the average discovery delay is too long. Another asynchronous design [13] used directional transmitters and omnidirectional receivers but could not guarantee discovery within a bounded time. Because all of these protocols involve oblivious neighbor discovery, they result in very long discovery times. In [14], a discovery algorithm was proposed where the nodes switch rapidly between transmitting and receiving modes. Assumption of GPS-clock synchronization is key to this highly directional LOS discovery method. Similarly, protocols which involve selecting transceiver positions randomly cannot guarantee that a neighbor will be discovered [7].

Additional studies have been made in attempt to reduce these discovery times by developing discovery protocols that are assisted by low bandwidth omnidirectional technology. In [15], a neighbor discovery method for a 3D drone network was proposed. The nodes scan the surrounding area in a specialized spiral path in order to ensure all neighbors are discovered. In [16], an FSO communication module was presented which was built using the help of MicroElectro Mechanical Systems (MEMs), consisting of programmable micromirrors used to align the directional beams.

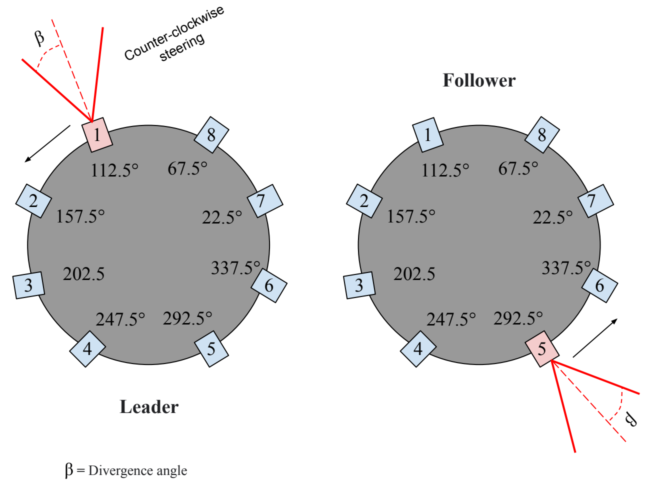


Fig. 2: Multi-transceiver FSO nodes.

We present a neighbor discovery method for a 2D ad hoc network that does not require GPS-clock synchronization. Coordination and spatial awareness of the nodes is directed by an omni-assisted long range channel. Our method ensures both bounded and minimal discovery times.

III. Proposed Discovery mechanism

In this section, we first present the assumptions and then describe the neighbor discovery method in detail.

A. Assumptions

- *Nodes:* Each node exists in a 2D ad hoc network. Each node can communicate within the range of its transceiver.
- *Directional transceivers:* Each node has a circular structure equipped with multiple directional FSO transceivers The number of transceivers is dependent on the width of the communication beam which is modeled as the divergence angle β in Figure 2. The transceivers are laid out to cover all directions for transmission and reception to achieve maximum spacial coverage.
- *Electronic beam steering:* The direction of a node's transmission/reception is accomplished by activating a specific transceiver at a specific time.
- *Omni-assisted channel:*. In the beginning of the neighbor discovery process, an additional side-channel (LoRa) is used to synchronize the LOS discovery using the FSO transceiver. LoRa provides a throughput of less than 20 KBps [8], which can not provide a sufficient data rate to carry out main communication.
- *Compass:* Each node is equipped with a compass in order to determine the direction/transceiver using which it will begin scanning the surrounding space. We are not relying on GPS information because it works poorly inside a building and the precision is not very accurate.

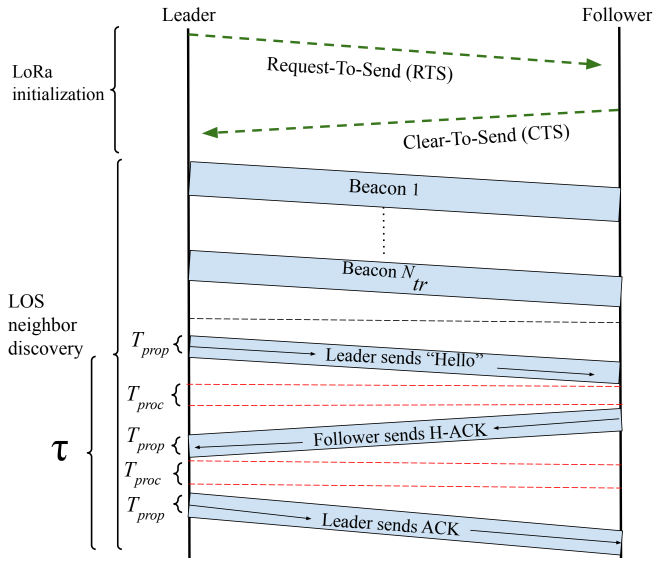


Fig. 3: Timing diagram of neighbor discovery.

B. Determining the number of directional transceivers

The number of transceivers on a given node is determined by the beam width of the transceiver. The smaller the beam width, the more transceivers are required in order to ensure that the entire 360° space surrounding the node has communication coverage. This way, if a neighboring node exists, other nodes will be able to find it, regardless of its position in the 2D space. For example if the divergence angle of the beam is β, we can determine the number of required transceivers as follows:

$$N_{tr} = \lceil (360/(2 \times \beta) \rceil, \quad (1)$$

The angle at which the center line of these transceivers should be placed is determined as:

$$\theta_i = i \times \frac{360}{N_{tr}} + \beta, \quad i = 1, 2, ..., N_{tr}. \quad (2)$$

Therefore, for $2\beta = 45°$, each node should have eight transceivers at angles 22.5° , 67.5° , 112.5° , 157.5° , 202.6° , 247.5° , 292.5° and 337.5°. This is modeled in Figure 2

C. Discovery Initiation

In this section, we describe the proposed omni-assisted neighbor discovery protocol. Algorithm 1 describes protocol. In the initialization phase, a node initiates the communication through the supplementary omnidirectional channel to send an request-to-send (RTS) beacon message. If another neighbor node exists in the vicinity, upon receiving the RTS, the neighbor sends back a clear-to-send (CTS) acknowledgement. Figure 3 depicts the timing diagram of the LoRa initialization phase in the top portion of the diagram. Once the existence of a neighboring node is found, the LOS neighbor discovery process, depicted in the bottom segment of Figure 3 can begin. In the subsequent sections we describe the process of discovering a single neighbor and then discovering multiple neighbors.

Algorithm 1: Neighbor Discovery using a omni-directional helper channel

```
Leader sends RTS and waits for CTS
if Leader receives CTS then
   Divergence Angle β
   Number of transceivers N_tr
   leaderAngle ← 1
   followerAngle ← ⌊(N_tr+1)/2⌋
   while i ≤ N_tr do
      Leader sends "Hello" and waits for "H-ACK"
      if Leader receives "H-ACK" then
         Reply with "ACK" and Stop
      end if
      Follower waits for "Hello"
      if "Hello" received by Follower then
         Reply with "H-ACK" and wait for "ACK"
         if ACK is received by Follower then
            Follower Stops
         end if
      end if
      leaderAngle + +
      followerAngle + +
   end while
end if
```

D. Discovering a Single Neighbor

In the LOS neighbor discovery phase, the Leader node begins scanning by activating the transceiver facing north and transmitting a beacon message. It transmits a *Hello* beacon through FSO transceiver and wait for *H-Ack* for a wait period. If it does not receive any *H-Ack*, it switches to the adjacent transceiver in a counter-clockwise fashion, hence the term electronic switching/steering. Similarly, the Follower node activates its transceiver facing south for a wait period and repeats the process for the adjacent transceivers. The Leader continuously sends a *Hello* message in the direction it is transmitting and waits for a response. The Follower waits to receive the *Hello* message. Once the beams are aligned (i.e. the transceivers face each other in LOS), the *Hello* message can be received by the Follower and it will stop scanning. The Follower then sends an *H-Ack* message back to the Leader. When the Leader successfully receives an *H-Ack* message in return, it also stops scanning. Finally, the Leader sends a last acknowledgment message, *Ack*, back to the Follower. The completion of this three-way handshake confirms that neighbor discovery is complete. In Figure 2, the transceivers are numbered 1 to N_{tr}, in order to portray the cyclical activation of transceivers. Here, the Leader node begins by activating transceiver 1 and the Follower nodes begins by activating transceiver 5.

E. Defining the Three-Way-Handshake Time

The three-way handshake time τ comprises the time for the Leader to send the *Hello*, the Follower to send an acknowledgement, *H-Ack*, back to the Leader, and the Leader to send the *ACK* back to the Follower, packet transmission delay, and packet processing delay. Thus, τ can be modeled as:

$$\tau = T_{tran} + 3 \times T_{prop} + 2 \times T_{proc}. \quad (3)$$

Here, T_{tran} is the transmission delay, T_{prop} is the propagation delay, and T_{proc} is the packet processing time.

F. Simultaneously Discovering Multiple Neighbors

In order to account for scenarios in which more than two nodes are present in the network, we use an iterative approach to discover all the neighbors. After the initialization through LoRa, the node with the highest ID is assigned as the *Leader* and all the other nodes are *Followers*. The Leader begins the LOS discovery as the transmitter and the Followers act as receivers. Leader election algorithms in distributed environments is a very well studied topic and falls outside the scope of this paper [17], [18]. In our discovery mechanism, a Leader can be assigned in two ways. Firstly, by selecting the node which initiates the communication through LoRa, or, by selecting the node with the lowest ID number. Following the similar scanning and three-way handshake process as in the previous subsection, the Follower is able to find all of the neighbors in one scan. After the first scan, the algorithm appoints a new Leader from the Follower nodes. The Follower node with the lowest ID number is made the new Leader. The scanning algorithm will continue in this way until all neighbors discover each other. The Multiple-Neighbor discovery method is presented in Algorithm 2.

Algorithm 2: Discovering Multiple Neighbors

```
Divergence angle β
Number of transceivers N_tr
leaderAngle ← 1
followerAngle ← ⌊(N_tr+1)/2⌋
followers ← an array of all follower nodes
neighborsfound = 0
visited ← emptyarray
if i > 0 then
    APPEND leader to followers
    leader ← followers(0)
    REMOVE followers(0) from followers
end if
while j < transNum do
    for s in followers do
        if leader can communicate with s then
            if !(s in visited) then
                Leader sends "Hello"
                if "Hello" received then
                    reply with H-ACK and wait for ACK
                    if ACK is received then
                        APPEND s to visited
                        neighborsfound++
                    end if
                end if
            end if
        end if
        if neighborsfound ≥ n − 1 then
            TERMINATE
        end if
        leaderAngle++
        followerAngle++
    end for
end while
```

IV. EVALUATION

To test our model with certainty, a simulation of the protocol is run using python over thousands of different trials. The simulation is designed to consider a variety of different node locations, distances and beam widths in order to ensure the functionality of the protocol. The results of our proposed simulation are compared to the results of two state-of-the-art protocols as described below.

A. Benchmark protocols

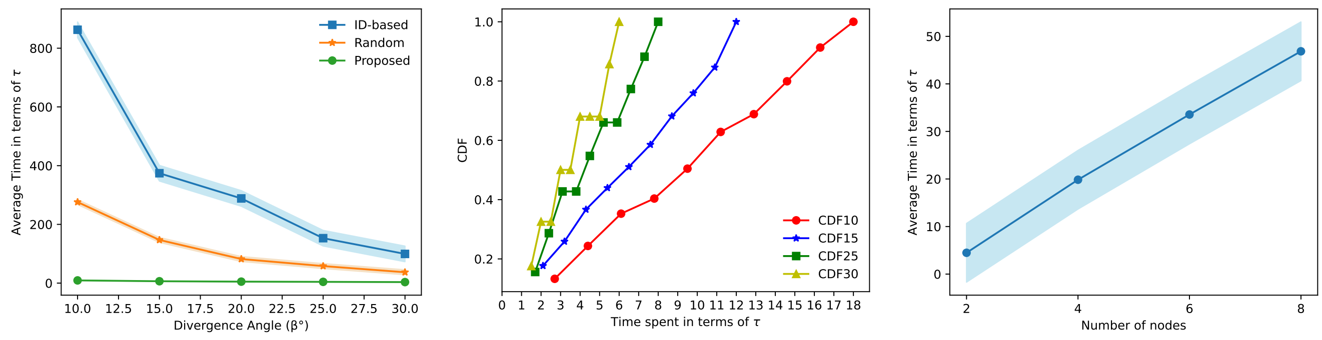
We have simulated a random-based neighbor discovery algorithm which have used to compare our proposed algorithm [7]. The random based discovery tests a random pair of transceivers until a neighbor is found. This algorithm takes longer than our proposed algorithm and it also does not guarantee that a neighbor will be found. Because of its arbitrariness, it is necessary to run the simulation 1000 times for each divergence angle width in order to get at least one successfully discovered neighbor. Consequently, as the beam width becomes smaller, the algorithm tries more pairs of transceivers until a neighbor is discovered, resulting in a longer discovery time. This is modeled in Figure 4a. Unlike our proposed model, which guarantees a discovery slot time of at most the number of transceivers, a successful discovery is not guaranteed on every run.

Similarly, we compared our proposed algorithm to an ID-based neighbor discovery algorithm which is guaranteed to successfully discover a neighbor in at most the ID length in slots [6]. Each node has an ID of binary digits where 0 corresponds to receiving and 1 corresponds to transmitting. The nodes will follow the ID sequence until the length of the ID. Figure 4a reveals that, because this particular protocol assumes that the nodes are oblivious to one another, it takes considerably more time than the proposed algorithm and the random-based protocol.

B. Results for discovering a single neighbor

To test our proposed algorithm, 1000 runs of the algorithm were completed for a series of different beam widths[1]. These runs considered the scenario in which a node has only a single neighbor. As presented in Figure 4a, the average discovery time increases, as the beam width narrower. This is an expected result as our beam covers less area, we will need to add more transceivers and therefore check more positions. In addition to the average discovery times, Figure 4b displays the cumulative probability distribution for the series of beam widths has also been plotted. In both graphs it is evident that as the beam width increases the discovery time decreases. When compared to both of the oblivious benchmark protocols, our model with omni-assisted discovery is faster. For a divergence angle of 10^o, the proposed algorithm achieves 99.42% and 98.19% reduction in discovery time compared to the ID based [6]

[1]The code is available at https://github.com/wsl-miami/nd-simulation



(a) Discovery time vs Divergence angle (b) CDF of neighbor discovery (c) Discovery time involving multiple nodes

Fig. 4: Average and CDF of discovery times for different divergence angles, single neighbor discovery and multiple neighbor discovery.

and random based protocol [7], respectively. For a divergence angle of 30^o, the reduction is 98.38% and 95.68% for ID based and random based, respectively.

C. Simulation for discovering multiple neighbors

The proposed simultaneous multiple neighbor discovery algorithm (described in Section III-F) is simulated to account for scenarios which involve more than one neighbor. Multi-neighbor discovery is conducted using an iterative ID-based approach. Completion of multi-neighbor discovery is defined as the time it takes for all nodes in the system to discover its neighboring nodes. In this variation, each node has a unique ID number. Multiple-neighbor discovery dictates that each node in the system is able to communicate with each one of its neighbors. Only the Leader is in transmission mode in each scan in order to avoid the problem of packet collision. If there is more than two nodes, the leader is able to find all of the nodes, which are followers, in one scan. Once a Follower has established communication with the leader, the follower ceases to scan in receiving mode. After the first scan, the algorithm appoints a new Leader among the Follower nodes. The follower node with the lowest ID number is made the new Leader. The scanning algorithm continues to search for the remaining nodes in this way until all neighbors are discovered by the current leader. Figure 4c portrays the average time taken for this to occur in for a varying number of total nodes. Using this approach, we can conclude that the time it takes to discover increases with a higher number of neighbors.

V. Experiments with Prototype

After all the rigorous simulation, in this section, we describe a prototype using off-the-shelf devices. First, we describe the prototype implementation and then present the experiment results.

A. Prototype

Figure 5 and Figure 6 depicts the schematic and the side view of the state-of-the-art prototype built using off-the-shelf components. We programmed the discovery protocol in python[2].

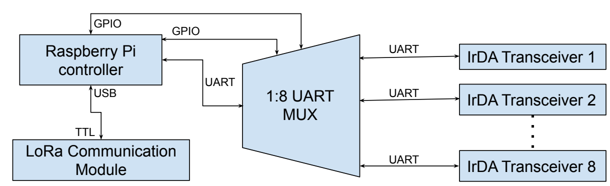


Fig. 5: Schematic of the prototype

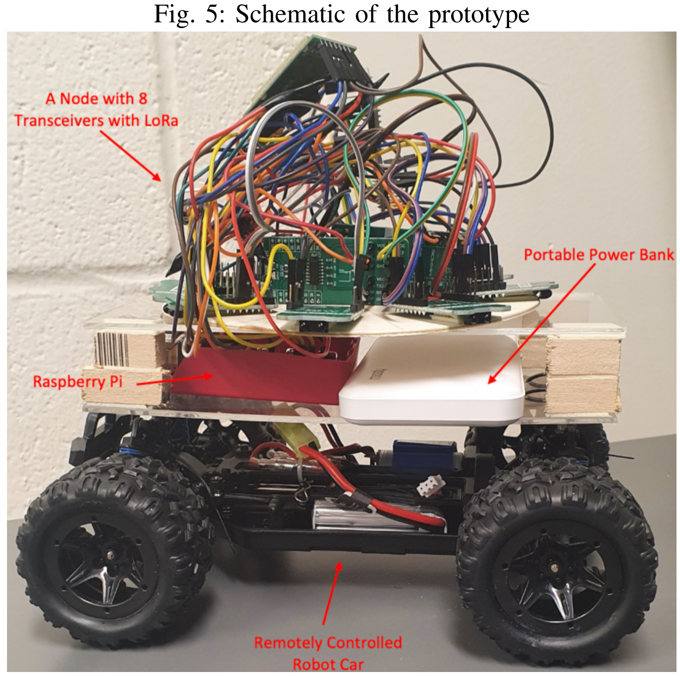


Fig. 6: Prototype of a multi directional transceiver with 8 IrDA transceivers, LoRa module and Raspberry Pi as the controller.

The system prototype consists of eight infrared transceivers, three UART [19] (universal asynchronous receiver-transmitter) multiplexers, a LoRa [8] communication module, and one Raspberry Pi as the controller. The IrDA [9] transceiver is an

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

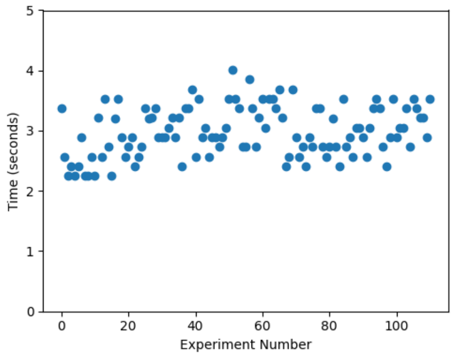


Fig. 7: Neighbor discovery time for each iteration of the experiment.

infrared transceiver which has one piece of integrated circuit for UART-IrDA conversion. Eight IrDA transceivers are connected to the MUX through UART. Two dual 4-Channel UART MUXs/DEMUXs are used as follower MUXs for switching data for a total of eight IrDA transceivers, and a leader Mux is wired to Raspberry Pi through UART for switching data for the two follower MUXs according to communication needs. By this method, the data path is completely controlled through four GPIO ports(two ports are used for the leader MUX, the other two ports are shared by two follower MUXs) of Raspberry Pi. Above is the wiring method used to control the IrDA transceiver to complete the communication. The LoRa communication module can communicate directly with the USB port of raspberry Pi. The LoRa communication module connects to the serial USB port of Raspberry Pi by using a USB to TTL converter.

B. Experiment results

This section discusses the result of over 110 experiments conducted using the system prototype. The results are plotted in Figure 7. Note that we are using UART-based serial communication for sending packets through IrDAs. To tackle several delays associated with the MUX, IrDA, etc., we force the nodes to wait for 160 ms before switching to the next IRDA. This makes the τ higher. The average time for discovery over these experiments is approximately 2.985 seconds. In the future, we aim to reduce this latency by optimizing the UART communication and finding a suitable waiting time.

VI. Conclusion

Neighbor discovery is a widely studied topic in wireless mesh networks. Neighbor discovery becomes more challenging in directional communications as the nodes need to discover the line-of-sight with their neighbor. Both nodes need to steer their communication beam towards the neighbor for effective communication. Oblivious neighbor discovery, i.e., where nodes do not possess a priory knowledge of neighbor's location, is a well-studied topic for directional communication. In this paper, we propose a novel design for neighbor discovery with the help of a long-range low-bit rate omnidirectional helper communication channel. Through rigorous simulation and a proof of concept prototype using off-the-shelf equipment, we prove that the proposed protocol can achieve guaranteed neighbor discovery in a shorter time. We plan to extend our work to consider packet collision when discovering multiple neighbors. We also plan to design and develop a multi-transceiver FSO module for a 3D ad hoc network, as part of our future work.

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