Effective Transceiver Selection for Mobile Multi-Directional Free-Space-Optical Modules

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***Abstract*—Demand for wireless data has increased significantly with the adoption of smartphones. To satisfy this huge demand, mobile operators are investing money and upgrading their infrastructure from 3G to 4G. However, it is expected that the demand will always stay hungry for more capacity and energy. This demand drives the need for alternate and complementary technologies in wireless communication. Free-space-optical (FSO) communication has the potential to serve as a complementary technology to RF for the future wireless networking. As a promising approach, multi-element spherical modules covered with multiple highly directional FSO transceivers has been shown to work well to handle mobility for FSO communication. Among other issues, the directionality of FSO communication necessitates a key problem to be solved in such modules: Maintaining the line-of-sight (LOS) among the mobile modules during an ongoing transmission. For FSO modules with many transceivers, reducing the modules' energy consumption becomes a crucial issue for the practicality multi-element FSO designs targeting mobile and ad-hoc settings. Although activating more transceivers on a module makes it easier to maintain LOS alignments between mobiles, it clearly uses more energy. In order to address explore tradeoff, this paper presents energy efficient mechanisms that aim to select an optimal subset of the directional transceivers in FSO modules.**

***Index Terms*—Free-space-optics; mobile ad-hoc networks; spherical FSO modules; channel selection algorithms**

I. Introduction

Recent proliferation of wireless technologies and choices available to user applications have triggered a tremendous wireless demand, and the wireless nodes are expected to dominate the Internet soon [1], [2]. The availability of wireless resources as substrates has caused an ever-increasing variety of applications. Recent reports show that usage of mobile Web [3] and Wi-Fi by smartphones is increasing sharply. Accommodating this growing wireless demand with cellular capacity does not seem possible in the long run. Further, the capacity gap between radio frequency (RF) wireless and optical fiber (wired) network speeds will remain huge because of the limited availability of RF spectrum. As the RF spectrum is getting scarcer, the push for more wireless bandwidth is driving wireless technologies in alternative spectrum bands into the networking field [4]. Free-space-optical (FSO), a.k.a. optical wireless, communications has been one of these technologies complementary to the traditional RF.

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Particularly within the military communications and networking context, solutions against RF interference are of high need. RF technologies are easy to intercept and jam, mainly due to the fact that RF signals propagate omni-directionally. This omni-directionality also brings in difficulty in spatial reuse, again descending to the limitations originating from RF interference. Even though recent advent of directional RF antennas is a promising approach for solving these spatial reuse and RF interference issues, their form factors are larger than FSO transceivers.

However, FSO is highly vulnerable to mobility due to its high sensitivity to line-of-sight (LOS) alignment as well as atmospheric attenuation. Recent research has shown that FSO mobile ad-hoc networks (FSO-MANETs) can be possible by means of "optical antennas" [5], i.e., FSO spherical structures covered with optoelectronic transceivers each of which is pointing to a different direction. Such FSO spherical structures achieve *angular diversity* via spherical surface, *spatial reuse* via directionality of FSO signals, and are *multi-element* since they are covered with multiple transceivers (e.g., LED and photo-detector pair). By using the directionality of FSO transceivers unlike the traditional mechanical steering mechanisms for LOS management, it is possible to use a simple handshaking protocol to "electronically steer" the LOS alignment onto the correct transceiver by using such spherical FSO structures [6].

The idea of "electronic steering" necessitates a selection mechanism for the transceivers since activating many transceivers for the LOS detection and alignment of neighbor nodes on a spherical FSO node is not energy efficient. When multiple transceivers are deployed on a spherical FSO node, maintaining the energy consumption in realistic regions is a major problem. Another problem is the hardware limitations of the current controllers. Providing a transmission medium for multiple transceivers requires many I/O interfaces since implementing many I/O interfaces on a controller board is not cost effective. Such systems may not be scalable when packaging multiple transceivers on a spherical structure. The selection strategy becomes more challenging when this limitation is considered for an ad-hoc environment where many FSO nodes with multiple transceivers are communicating with each other. Therefore, the challenge is to select an *optimal subset* and to decide on an *optimal order/schedule* of how to

incorporate the transceivers in the network for fast and efficient alignment.

Selection strategy of the transceivers must also maintain the LOS alignment under disruptions that are caused by the mobility of the communicating nodes since there is an uncertainty of the locations of the mobile nodes in 3-D space. In such scenarios, the technique of the determining uncertainty can be based on approximations by different distribution models such as Gaussian distribution. There is also need for smart and fast selection mechanisms that will select the optimal subset of transceivers to establish the alignments between the neighbor nodes. In this paper, we propose two different selection mechanisms to solve such problem. We show that it is possible to attain a good balancing of the tradeoff between better LOS alignment and higher energy efficiency. Specifically, we show that our transceiver selection mechanisms can maintain high throughput of the FSO network with an order of magnitude less energy consumption.

The rest of the paper is organized as follows: In Section II we review the literature for transceiver selection mechanisms. In Section III, we present our design of transceiver selection mechanisms and simulation results in mobile ad-hoc scenarios. We provide a thorough simulation study where we investigate the effect of divergence angle, number of transceivers, and alignment interval. We discuss our conclusions and future work in Section IV.

II. Background

There has been large body of work on 3-D tracking mechanisms in different research fields considering particle filtering at 3-D spaces and sensor query mechanisms that have some overlap with the concept of our work. The authors of [7] formulate the 3-D tracking problem with data fusion by extending 2-D bearing only tracking algorithm. The authors show that 3-D tracking can be done by applying multiple 2-D fusions. The authors of [8] presents two different techniques: information-driven sensor querying (IDSQ) and constrained anisotropic diffusion routing (CADR), for energy efficient data querying and routing in ad-hoc sensor networks. As a result, authors conclude that IDSQ and CADR approaches are more energy efficient and tolerable to link failures. One possible problem in such techniques is the sensor selection can be redundancy in the information provided among available sensors in the network. The challenge is to select an *optimal subset* and to decide on an *optimal order* of how to incorporate these sensors in the network. In such scenarios, the technique of the determining uncertainty is based on approximations by a Gaussian distribution model. Other methods can also be used to define the uncertainty and design a system accordingly as proposed in their paper to remedy the problem of selection strategy.

FSO systems need high accuracy between the transmitter and receiver pairs in order to establish a reliable communication medium. This becomes more challenging when the mobility is also involved in an FSO scenario. Developing a reliable control system for data acquisition and tracking

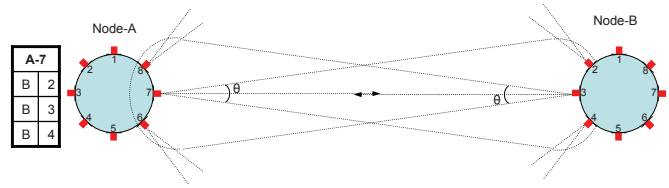


Fig. 1. Multi-element antenna design in 2D view and sample alignment table kept in interface 7 of node A. [10]

TABLE I
Table of default parameter values common to each simulation set in our experiments. [10]

Parameter Name	Default Value
Number of nodes	49
Number of flows	49x48
Visibility	6 km
Number of interfaces	8, 16
Mobility	1 m/s
Simulation time	3000 s
Transmission range and separation between nodes	30 m
Area	210 m by 210 m
Node radius	20 cm
Divergence angle	0.5 rad
Photo detector diameter	5 cm
LED diameter	0.5 cm

transceivers for establishing alignments on an FSO node is a certain challenge. Tracking a mobile FSO receiver is mainly implemented considering beam steering mechanisms by adjusting beam divergence as an alternative to mechanical steering mechanism [9]. The need for a novel control system without expensive mechanical devices has always been under research. Our work follows this direction of research and aims to perform LOS tracking/management via electronically steering data transmissions across transceivers with minimal energy consumption.

III. Transceiver Selection

We consider an FSO module with many transceivers on it and aim to design a transceiver selection mechanism that detects and maintains LOS with neighbor modules. We aim to perform this LOS management in a distributed way where each module operates autonomously. We do assume availability of simple handshaking with neighbor modules. Such handshaking allows the modules to detect which neighbor is aligned with transceivers. Proof-of-concept for this simple handshaking protocol for LOS management was shown in [6]. As illustrated in Figure 1 in 2D view, tracking and maintenance of LOS alignment between two multi-transceiver modules is achieved via "alignment tables" that map each transceiver to a neighbor module's transceivers. We, then, use these tables to determine

Algorithm 1 Transceiver Selection Algorithms

```
SINGLE MODE ALIGNMENT ROUTINE :
UPON The Event of Single Mode Alignment :
for all Interfaces of the node do
    Send search message from the interface
    if The interface received ACK from a different node then
        Update interface alignment table as depicted in Figure 1
    end if
end for
MAINTENANCE ROUTINE :
UPON the event of maintenance :
for all Interfaces of the node do
    Retrieve alignment table
    for all Interfaces in the alignment table do
        Send search message from the interface
        if the interface received ACK from the currently aligned node interface then
            Continue
        else
            Send search message from the next-interface
            if the next-interface received ACK then
                Update next-interface alignment table as depicted in Figure 1
            end if
            Send search message from the previous-interface
            if The previous-interface received ACK then
                Update previous-interface alignment table as depicted in Figure 1
            end if
        end if
    end for
end for
TWO MODE ALIGNMENT ROUTINE :
UPON time to perform discovery interval : SINGLE MODE ALIGNMENT ROUTINE
UPON time to perform maintenance interval : MAINTENANCE ROUTINE
```

which transceiver to utilize when there is a packet destined to a neighbor.

Establishment and maintenance of these alignment tables become costly if there are many transceivers. The cost is not just only in terms of handshake messages to be exchanged but also, and more importantly, the amount of total energy needed. Keeping the transceivers active and exchanging the handshake messages through them can quickly become prohibitive in terms of energy consumption if the number of transceivers is too large and all of them are utilized for LOS management. We focus on this particular issue and aim to reduce the number of transceivers to be used/activated for LOS management protocol. The key challenge to tackle is *which transceivers should be activated to track the alignments more efficiently on a spherical FSO module*. Therefore, we focus on selecting an *optimal subset* of the transceivers and deciding on an *optimal order/schedule* of how to incorporate the transceivers in the LOS management protocol for fast and efficient alignment.

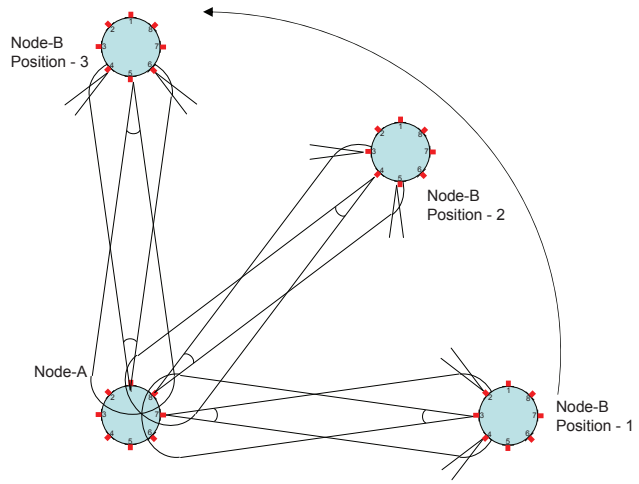


Fig. 2. Sample alignment scenario for two mobile nodes. [10]

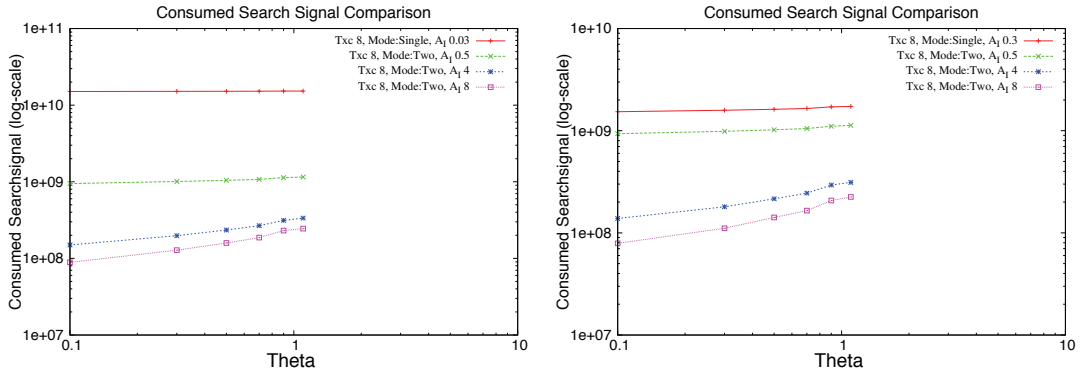
A. Selecting a Subset of Transceivers

Figure 2 shows what happens when a neighbor node B is moving around a node A. There are two important intuitions to observe from the scenario:

- *Movements of neighbors project to spatially correlated (or close) transceivers*. A key property of mobility to exploit is the fact that LOS alignment with a moving neighbor should be involving transceivers close to each other. In Figure 2, when node B moves from position 1 to 3, its LOS alignment on node A moves from transceiver $6 \rightarrow 7 \rightarrow 8 \rightarrow 1 \rightarrow 2$. This means when an LOS alignment to a neighbor is lost, one should be able to recover the alignment by just activating the transceivers close to the one where the LOS alignment was lost.
- *Significant number of transceivers are not relevant*. Another key point of leverage from the scenario in Figure 2 is that a lost of transceivers are not relevant to the existing LOS alignment. When node B is moving the transceivers 3, 4, and 5 are never to be used. This behavior could be very well utilized by stopping the LOS management protocol's handshake messages on those transceivers. However, these "irrelevant" transceivers should be invoked to discover LOS alignments with new neighbors.

Using the above intuitions, we separate the timescales of *discovery* and *maintenance* of the LOS alignments in our transceiver selection mechanism.

1) Single-Mode LOS Alignment: Under the baseline scheme, handshake messages (which include a search message and an acknowledgment message for each direction) serve both the purpose of discovering LOS alignment with a new neighbor as well as maintaining (or reaffirming) an existing LOS alignment. These handshake messages are exchanged



(a) Discovery interval times: 0.03, 0.5, 4, and 8 seconds- Maintenance interval time: 0.03 seconds.

(b) Discovery interval times: 0.3, 0.5, 4, and 8 seconds- Maintenance interval time: 0.3 seconds.

Fig. 3. The number of consumed search signals for 8 transceivers: Single-mode vs. Two-mode alignment.

when the interval timer fires. This scheme does not separate the discovery and maintenance and sends a search signal from every transceiver when the interval timer fires.

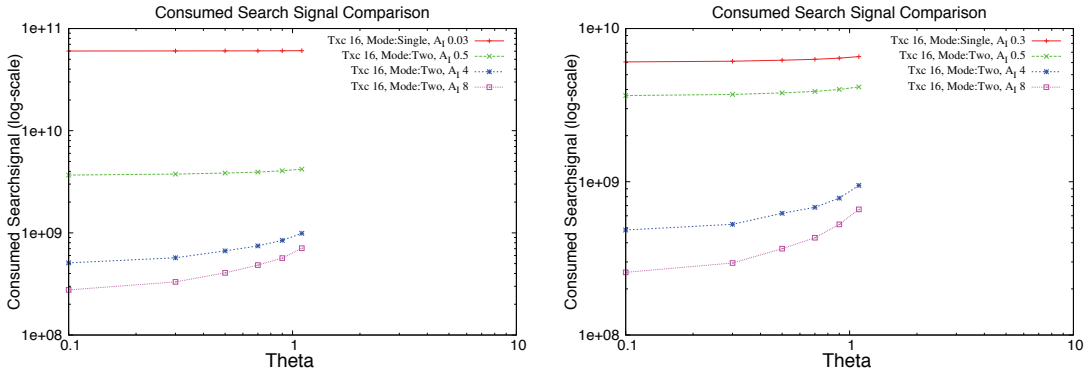
2) Two-Mode LOS Alignment: Intuitively, the discovery of new LOS alignments could be made at larger timescales. So, we separate the two modes. For maintaining an existing LOS alignment, we keep track of alignments in each period and check if the alignment still exists in the next period. Since we are already maintaining alignment tables, this check is not costly. Further, it allows us to use the first intuition we observed from Figure 2 and send the search message only at the transceivers next to the one where the alignment was lost. This will save a lot of search messages when compared to the Single-Mode scheme where search messages are sent from all physical transceivers deployed on a node. Algorithm 1 summarizes our single-mode and two-mode transceiver selection algorithms.

One problem can be detecting new possible alignments in the environment, since we only deal with the previous and next neighbor of the aligned transceivers. Thus, we also send search signal from all transceiver periodically to perform the discovery of new LOS alignments. This could be done at a larger timescale, a.k.a. *discovery interval*, when the interval timer fires, all of the FSO nodes in the environment send search message from their corresponding transceivers to seek possible alignments. If alignment is detected each node updates its alignment table with new LOS alignment information.

3) Tuning Timescales: To make alignment more efficient, we increase discovery alignment timer value and we keep the maintenance interval at a fixed value and smaller than discovery interval. Therefore, we decrease the number of search signals that are sent totally which reduce total power consumption and interference caused by search signals that are periodically sent over each transceiver at every node. The main goal of the maintenance interval is to keep the alignment alive by sending search signal from the closest neighbors of the transceivers when the current alignment is lost. Therefore, we define a specific time interval to maintain the alignments: maintenance interval. At each interval, nodes check if they keep alignment alive from the previous alignment condition. If the alignment is lost, the search signal is sent from previous or next neighbor of the transceiver which were aligned previously. If one of the neighbor nodes detects the alignment, it updates its alignment table for the alignment information. This procedure is done for every transceiver that has an alignment information in the alignment table. Second goal of the maintenance interval is to reduce the number of alignment search signals. Instead of sending alignment request from all transceivers, in the maintenance interval, search signals are sent from a number of specific transceivers (in this situation just the neighbor of the aligned transceivers) to keep alignment status alive. Therefore, number of alignment search signals is reduced significantly. This improvement provides less power consumption because most of the wireless systems consume power when they are in the search phase.

Since the maintenance phase only keeps alignments alive, there should be a mechanism to detect new nodes in the environment. Therefore, the primary purpose of the discovery interval is to detect new nodes in the environment and establish new alignments. The module seeks for new alignments at every discovery interval. Every transceiver in each node/module sends search signal and searches for the transceivers that are in line-of-sight of each other. If alignment exists, the node updates its alignment table.

In single-mode alignment operation, the maintenance and discovery procedures are performed at the same time scale, where we send search signal from all transceivers on an FSO node. Single-mode operation can provide better alignment detection since all the transceivers are active at the interval time. However, the major disadvantage of this mode is being inefficient to power consumption and interference because of the search signals that is being dissipated. In two-mode alignment operation, maintenance and discovery procedures are performed at different time scales. The main goal of this operation is to reduce the number of active transceivers and search signals in the search phase.



(a) Discovery interval times: 0.03, 0.5, 4, and 8 seconds- Maintenance interval time: 0.03 seconds.

(b) Discovery interval times: 0.3, 0.5, 4, and 8 seconds- Maintenance interval time: 0.3 seconds.

Fig. 4. The number of consumed search signals for 16 transceivers: Single-mode vs. Two-mode alignment.

B. Simulation Results

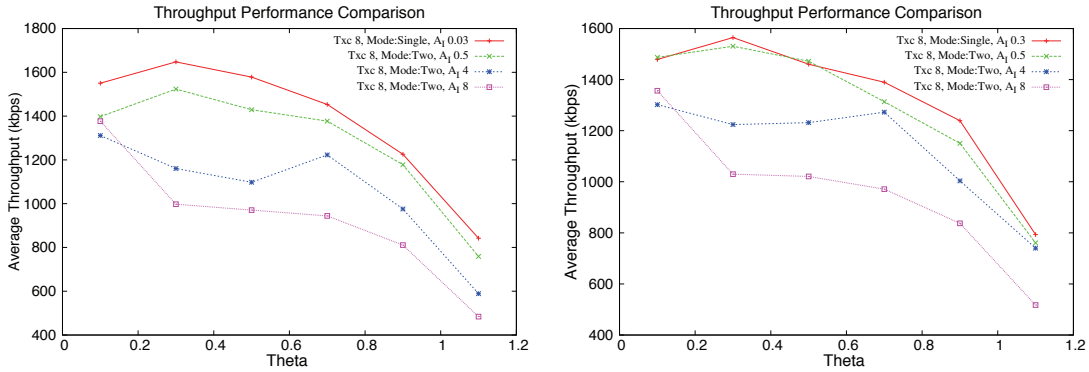
The selection strategy must also satisfy the maintenance of the LOS alignment under disruptions that are caused by the mobility of the communicating nodes since there is an uncertainty of the locations and movements of the mobile nodes in 3-D space. Therefore, we focus on transceiver selection algorithms and evaluate which mechanism is better by measuring the aggregate network throughput performance. In our simulation-based evaluations, we adhere to FSO propagation and transmission models in NS-2 proposed by Bilgi in [10]. We base our simulations on circular FSO nodes and deploy FSO transceivers on such nodes.

In single-mode alignment detection scheme, the discovery and maintenance interval times are both set to 0.03 and 0.3 seconds. In the two-mode alignment scheme we increased discovery interval times to 0.5, 4 and, 8 seconds and keep the maintenance interval values at 0.03 and 0.3 seconds. We conduct the simulations for different number of transceivers respectively 8 and 16. Simulations include 49 nodes. Nodes are positioned in a 7x7-grid view at start time and they are mobile during the simulation. Nodes open FTP file transfer sessions using TCP to every other node in the network. Therefore, in the simulations there are 49x48 flows in total. All nodes are mobile moving at 1 meter per second with random waypoint mobility model. We used an area of 210x210 meters and the visibility of the medium was 6 kilometers. We ran the simulations for 3000 seconds and repeated in simulations for 10 iterations with different seed values. We compare FSO performance between single-mode and two-mode alignment schemes under the same conditions. We aim to answer the following research questions: How effective the two-mode alignment detection mechanism is compared to the single-mode alignment in terms of power consumption and end-to-end throughput?

Table I shows the *default* parameters we use in our simulations. The FSO node structures are circular in shape. Transceivers are placed on the nodal shape with a deterministic separation, i.e., the distance among any two-neighbor transceivers is the same. The node structure has a radius of 20 cm. The LEDs have 0.5 cm and PDs have 5 cm radius.

Figures 3 and 4 show the number of search signals sent at varying maintenance and discovery intervals for single-mode and two-mode alignment schemes and different interface counts. Since most of the power is consumed at the search/discovery phase, we define the number of search signals as power the consumption metric. As shown in Figures 3 and 4, the two-mode alignment scheme consumes an order of magnitude less power compared to the single-mode alignment scheme. The difference between the two schemes does not seem to be affected noticeably when the divergence angle, θ, varies. Figures 5 and 6 show the throughput performance at varying maintenance and discovery intervals. The number of transceivers changes from 8 up to 16 and we increase the divergence angle from 0.1 radian to 1.1 radians. One must note that, as we increase the divergence angle of transceivers the coverage area of a node starts to resemble to that of RF. If the divergence angle is further increased, adjacent beams on a node start to overlap and cause crosstalk and interference. This is why we see a decrease in the overall network throughput in Figures 5 and 6.

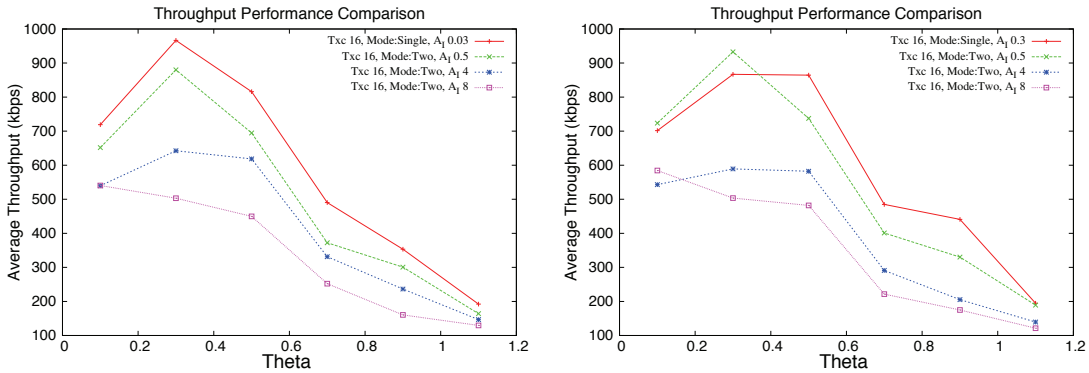
When the discovery interval time value is increased, we observe a throughput decrease. Our conclusion is that especially the decrease in throughput is not dramatically affected with larger timer intervals. This is an important finding to reduce the re-alignment overhead. However, compared to number of consumed search signals at single-mode alignment, one must note that, there is a tradeoff between the power consumption and throughput. Throughput does not decrease dramatically, however we observe a significant decrease in the search signals sent. Therefore, the two-mode alignment scheme performs better compared to the single-mode scheme, and presents a good tradeoff between throughput and power consumption. The best throughput performances are observed with 8 transceivers and when the theta value is 0.3 radian. Increasing the number of transceivers in our scenario did not increase the throughput performance because of the severe crosstalk and interference. For better results, different deployment scenarios and theta values should be considered as we only focus on 7x7 grid topology in an area of 210x210 meters.



(a) Discovery interval times: 0.03, 0.5, 4, and 8 seconds- Maintenance interval time: 0.03 seconds.

(b) Discovery interval times: 0.3, 0.5, 4, and 8 seconds- Maintenance interval time: 0.3 seconds.

Fig. 5. Average network throughput with 8 transceivers per node: Single-mode vs. Two-mode alignment.



(a) Discovery interval times: 0.03, 0.5, 4, and 8 seconds- Maintenance interval time: 0.03 seconds.

(b) Discovery interval times: 0.3, 0.5, 4, and 8 seconds- Maintenance interval time: 0.3 seconds.

Fig. 6. Average network throughput with 16 transceivers per node: Single-mode vs. Two-mode alignment.

IV. Conclusion

In this paper, we presented our contribution to the NS-2 network simulator, mainly on the transceiver selection mechanisms for multi-element free-space-optical structures. We assessed the efficiency of varying simulation parameters on the overall network throughput for different alignment detection and maintenance schemes. Such algorithms are needed for dense packaging of FSO nodes to make FSO systems applicable to real world scenarios. We conclude that the new transceiver selection schemes with multiple modes of operation perform better than our previous alignment scheme. Further, different selection mechanism are also possible for different deployments and environmental conditions.

Acknowledgement

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