Overcoming Alignment Delay in RF+FSO Networks

Michael Atakora and Harsha Chenji
School of Electrical Engineering and Computer Science, Ohio University, USA
ma136412, chenji@ohio.edu

***Abstract*—The use of highly directional antennae in wireless networks has been shown to increase network capacity. As the beamwidth decreases, near perfect alignment is required to achieve these capacity gains. This becomes particularly challenging in mobile adhoc networks, leading to high alignment delay. In this paper, we explore ways of mitigating alignment delay in practical delay tolerant networks (DTNs) where each node has both a radio frequency (RF) control and a free space optical (FSO) data channel. We show that overcoming alignment delay while multicasting data during contact opportunities is an abstraction of the minimum weighted set cover problem. An optimal multicast scheme is implemented in a DTN simulator over a new session-based MAC protocol. Thorough performance evaluation demonstrates that we can compensate for fixed alignment delay, paving the way for high capacity DTNs.**

***Index Terms*—multicast; free space optics; set cover; alignment**

I. Introduction

The ideal mobile ad hoc wireless network is full duplex, highly directional, and free of interference, since the combination of these conditions leads to high capacity. Full duplex links alone do not double the capacity of a network [1], because of interference. The use of omni directional antennae in wireless networks leads to energy wastage and compromises security [2]. In contrast, the capacity of directional networks has been shown to be purely noise limited. While the capacity of arbitrary networks is $\Theta(W\sqrt{N})$ where W is the node transmitting capacity in bps and N is the number of nodes [3], directional networks enjoy a capacity gain [4] of $2\pi/\sqrt{\theta_1\theta_2}$, where θ_1 and θ_2 are the beamwidth of the sender and receiver. Reducing the minimum beamwidth θ of a directional radio frequency (RF) antenna to the 10^{-6} radian range greatly increases the complexity, since the size of the antenna is inversely proportional to the minimum beamwidth.

Laser-based free space optical (FSO) links, investigated since the 1970s, are full duplex, highly directional (θ on the order of tens of μrad), high capacity (data rates on the order of tens of Gbps), high bandwidth (several THz of license-free spectrum), and even possess security properties (low probability of interception/detection). A major roadblock to the adoption of FSO is that in practice, a very small θ requires complex pointing, acquisition and tracking (PAT) to create and maintain the link. Because of the high directionality, a very large beam alignment delay d_{al} component is added to the data delivery delay. $d_{al} \approxeq$ 100s for satellite links [5] where $\theta \approxeq 40\mu rad$, while d_{al} is negligible for omni directional RF.

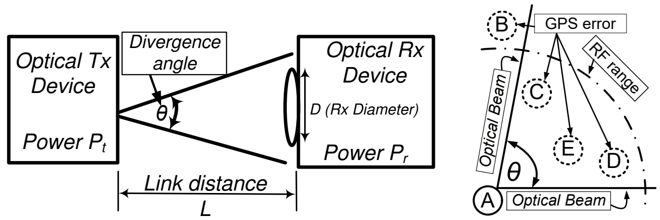
Unfortunately, FSO data rates ($\propto \theta^{-2}$) [6] are very high precisely because θ is very small. Thus, there is a fundamental tradeoff between data rate and alignment delay. This problem is not very apparent in point-to-point links where d_{al} is incurred *only once* when the link is initially setup - thus, a d_{al} of a few seconds is usually acceptable for short range links. This d_{al} is incurred *multiple times* in mobile ad hoc multi-hop wireless networks where senders frequently talk to multiple receivers (e.g., during multicast). This is the *hidden cost* to be paid for the $2\pi/\sqrt{\theta_1\theta_2}$ factor capacity gain.

In this paper we build upon our previous work [7], where we proposed a solution for overcoming d_{al} in FSO multicast: the θ-based tradeoff between data rate and alignment delay is exploited by dividing the receivers into multiple sets, which are chosen such that the combination of data delivery and alignment delays are minimized, thus maximizing overall throughput. In this paper, we investigate the effectiveness of this technique in a scenario where multicast is extremely important: delay tolerant networks (DTNs), which have low node densities but high node mobility. Node inter-contact opportunities are limited; for successful delivery of packets, DTN protocols rely on multi-copy routing [8], [9] and store-carry-forward approaches. By replicating a packet onto multiple nodes (i.e., multicast), the packet delivery probability is increased, as is the contact bandwidth. It is well known [10] that the contact bandwidth influences the performance of a DTN. Since DTN nodes are mobile, contact periods should be fully optimized to reduce data loss as a result of misalignment or the node moving out of radio range. FSO is a suitable candidate as a traffic channel for such applications due to its high bandwidth. Therefore, this FSO multicast solution is essential for DTNs where FSO is used as the data channel.

To the best of our knowledge, apart from our previous work in [7], optimal multicast in such hybrid RF/FSO DTNs has not been investigated. The rest of this paper is organized as follows: we put our work in context with related efforts in Section II. In Section III, we present a brief review of the optimal multicast algorithm. A new session-based medium access control (MAC) protocol that implements this optimal multicast algorithm is discussed in Section IV, as well as how it can be adapted to accommodate different DTN routing protocols. An evaluation of the various multicast schemes is presented in Section V, after which we provide a conclusion.

II. Related Work & Contributions

Hybrid RF and FSO techniques are popular not only in DTNs, but also in backhaul networks [11], [12], [13]. This paper focuses on RF+FSO DTNs and ad hoc networks in general, but the presented techniques can be easily extended to other networks. There is a large body of work regarding RF-only DTNs. To exploit the benefits of multicasting, several



(a) FSO Link (b) Hybrid RF/FSO Net.

Fig. 1: (a) Illustrating the various FSO link parameters for a single point-to-point link: P_t, P_r, L, θ and D. (b) A hybrid RF/FSO network where node A communicates with nodes C, D & E with a FSO beam divergence angle of θ. Node A is unaware of node B since it is outside of A's RF radio range.

enhancements have been proposed to RF-only routing protocols. Situational awareness is leveraged in [14] to develop a tree-based multicast scheme whereby nodes build up trees rooted at themselves to each and every destination. Multicast and broadcast algorithms for ad hoc networks with directional RF antennas have also been investigated. In [15], the authors develop and evaluate broadcast and multicast heuristics for a network consisting of power constrained devices using tree construction algorithms. This approach is not suitable for intermittently connected networks, since it is difficult to construct and maintain trees in networks whose topology is fast changing. In the area of FSO ad hoc networks, the authors of [16] introduce and implement a FSO node design in which spherical surfaces are tessellated with several transceivers to achieve near omnidirectional node coverage. This is achieved by means of an auto-alignment circuit that detects a loss of line of sight by electronically tracking optical beams. However, adaptive beam divergence angle is not addressed. In the area of FSO DTNs, the authors of [17] develop algorithms for networks with fragile links. The objective of such algorithms is the minimization of a transient information level metric defined to be a function of both the amount of information in the network and the projected physical distance to the destination subject to QoS constraints.

Our contributions are as follows: 1) We propose a new session-based MAC protocol for the implementation of optimal multicast schemes in hybrid RF/FSO DTN routing protocols and 2) In our proof of concept paper [7], we considered only instances where nodes were static. In this paper, we introduce node mobility.

III. Review of the Optimal Multicast Algorithm

In this section we review our optimal multicast algorithm from [7]. We provide a background into the FSO PHY, describe concepts such as broadcast and multiple unicast which ultimately lead us to formulating the FSO multicast problem. We then provide an exact solution and a faster but approximate greedy heuristic.

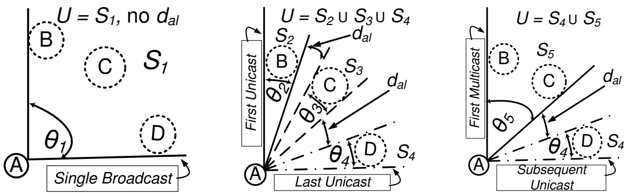
System Model:- The beam generated at the FSO source either diverges due to physical imperfections in the source, or can be made to diverge using a lens; this angle of divergence is defined as the *beam divergence angle* θ (Figure 1a). Given L as the Euclidean distance between the sender and receiver, the effective data rate R_b at a divergence angle of θ is expressed [6] as

$$R_b(\theta) = \frac{P_r}{hfN_b} = \frac{P_t D^2 L_{tp} L_{rp} \eta_t \eta_r 10^{\frac{-\alpha L}{10^4}}}{hfN_b \theta^2 L^2} \tag{1}$$

where P_t is the transmitted power, D is the receiver diameter, L_{tp} and L_{rp} are the pointing losses resulting from imperfect alignment of the transmitter and receiver respectively, η_t and η_r are the transmitter and receiver optical efficiencies respectively, α is the atmospheric attenuation factor, f is the frequency of the light source, h is Planck's constant and N_b is the detector sensitivity. The RF+FSO system model is shown in Figure 1b. The nodes ("A,B,C,D,E" in Figure 1b) are equipped with an omnidirectional RF radio as well as a directional FSO radio. Nodes broadcast their position over RF. We account for possible positioning errors (dotted line around nodes in Figure 1b), since GPS systems currently have a 3m position accuracy g 95% of the time. Therefore, nodes have to set θ such that the receiver is within the FSO footprint. Nodes outside the RF range ("B" in Figure 1b) are not considered as neighbors since their location cannot be obtained.

Broadcast vs. Multiple Unicast:- The fundamental building blocks to formulating the multicast algorithm are the concepts of broadcast and multiple unicast which are based on the ability to manipulate beam divergence and steer the laser transmitter. With broadcast (Figure 2a) the transmitter's θ is manipulated so that all receivers are within its footprint. In the case of multiple unicast (Figure 2b), data is sent to each receiver one at a time with non-zero alignment delay d_{al} accounted for. We define d_{al} as the time it takes a node to perfectly reorient it's laser transmitter in the direction of another node. We use our understanding of broadcast and multiple unicast to obtain all possible multicast combinations. We define a universe $\mathcal{U}$ of nodes that are to receive broadcast data. A *set* S_i is a group of nodes in the network whereby exactly one transmission is required to multicast to each of it's elements. It is noted that the union of all sets S_i should be equal to $\mathcal{U}$. A hybrid combination of sets is presented in Figure 2c whereby the first multicast transmission is a broadcast to B & C with the second transmission being a unicast to D.

The minimum number of multicast sets K can be derived by sorting receivers in order of decreasing azimuth ϕ from the origin (where node A is located) and observing that, whiles following a clockwise trajectory, if ϕ_i for node i is both less than and greater than ϕ for two nodes j, k in a set S_x, then node $i \in S_x$. Using this structure to enumerate all possible sets for a given $\mathcal{U}$ from Figure 2, we see that there is exactly 1 set of size 3 (S_1), exactly 3 sets of size 1 (S_2, S_3, S_4), and exactly 3 sets of size 2 (S_5, S_6 = $\{C, D\}$ and S_7 = $\{D, B\}$, S_6 & S_7 are not shown in Figure 2).Therefore generally, to broadcast to N nodes, there are exactly N sets of size 1 through to size $N-1$, and exactly 1 set of size N, for a total of $K = N^2 - N + 1$. The constructed sets lead us to the FSO multicast problem.



(a) A set with all receivers (B, C and D)

(b) A possible combination of sets

(c) Another combination of subsets

Fig. 2: Illustrating several set combinations in FSO multicast (a) a broadcast set with a FSO beam divergence angle of θ_1 (b) multiple (three) unicasts with divergence angles of θ_2, θ_3 and θ_4 (c) a hybrid of broadcast and unicast sets. The union of all sets in a diagram is always equal to the universe of nodes.

The FSO optimal multicast problem can be stated as follows: given a universe $\mathcal{U} = \{n_1, n_2, \ldots, n_N\}$ of N nodes, a collection $\mathcal{S} = \{S_1, S_2, \ldots, S_K\}$ of $K = N^2 - N + 1$ sets can be constructed. The cost of broadcasting data to a set S_i is the data delivery delay d_i which depends on R_b for that set, which in turn depends on the required θ. The objective is to find $\mathcal{S}' \in \mathcal{S}$ with minimum total delay such that all N nodes are covered. The delivery delay d_i for a set S_i is computed using the size of the broadcast data P, the minimum divergence angle θ_i required for all member nodes to be in the transmitter's footprint, and alignment delay d_{al}. Using Equation 1, d_i is calculated as

$$d_i = \max_j \left\{ \frac{P}{R_b(\theta_i)} + d_{al} \right\} \text{ where } 1 \leq j \leq |S_i| \quad (2)$$

where $R_b(\theta_i)$ is calculated for each node $j \in S_i$ using different values of distance L_j. We formulate the optimal FSO multicast problem as a 0/1 integer problem. Each set S_i is assigned a binary decision variable: x_i is 1 if $S_i \in \mathcal{S}'$, and 0 otherwise. The problem can now be formulated as follows.

Problem 1. *The Optimal FSO Multicast Problem*

$$\textit{minimize} \quad \sum_{i=1}^{K} x_i d_i \quad (3)$$

$$\textit{subject to} \quad \bigcup S_j = \mathcal{U} \quad \forall \quad S_j \in \mathcal{S}' \quad (4)$$

$$\textit{where} \quad S_i \in \mathcal{S}' \textit{ if } x_i = 1$$

In the objective (Equation 3), the delay d_i per set is the cost (Equation 2) of sending data to all nodes in that set. Equation 4 stipulates that each node has to be in at least one set.

Set Cover & Heuristic Solutions:- In this subsection, we translate the Optimal Multicast Problem into a weighted set cover problem. Formally, the minimum weighted set cover problem is as follows. Given a universe $\mathcal{U}$ of N elements, and a collection $\mathcal{S} = \{S_1, S_2, \ldots, S_K\}$ of sets whose elements are in $\mathcal{U}$, where each set S_i is assigned a weight w_i, the objective is to find a subset $\mathcal{S}'$ of $\mathcal{S}$ with minimum total weight such that each element in $\mathcal{U}$ exists in at least one set in $\mathcal{S}'$ (i.e., all elements are "covered"). We can easily see that the Optimal Multicast Problem is equivalent to the minimum weighted set cover problem.

Algorithm 1: Greedy Local Optimum Heuristic

Input: Location (x_i, y_i) for nodes n_1 **to** n_N, P, d_{al}
Output: Sets containing nodes in multicast group

```
1  for i ← 1 to N do
2      φ_i ← tan((y_i − y_0)/(x_i − x_0))
3  Sort nodes in clockwise order of φ_i to obtain n_1' to n_N'
4  j ← 1
5  S_j ← n_1'
6  for i ← 1' to N' − 1 do
7      if d_{i',i'+1} < d_i' + d_{i'+1} + d_al then
8          S_j ← S_j ⋃ n_{i'+1}
9      else
10         j ← j + 1
11         S_j ← n_{i'+1}
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Due to the computational complexity of solving the above integer program, we provide a greedy heuristic. The heuristic builds sets by greedily comparing the cost of broadcasting to that of multiple unicast to a pair of adjacent nodes. The delay $d_{i',i'+1}$ associated with broadcasting to a pair of adjacent nodes $n_{i'}$ and $n_{i'+1}$ is defined as the weight d (Equation 2) of a set $S = \{n_{i'}, n_{i'+1}\}$. Similarly, the delay $d_{i'}$ associated with unicasting to a node $n_{i'}$ is defined as $P/R_b(\theta_{i'})$. In lines 1 to 3, the sender sorts the receivers in clockwise order of azimuth ϕ_i from the origin (sender's location). A set is then created and the first node in the array of sorted nodes is placed in it (lines 4,5). In lines 6 to 11, the algorithm compares the delay associated with broadcasting to a pair of adjacent nodes to that of multiple unicast. Nodes are placed in sets depending on which scheme is cheaper (lines 8-11).

IV. Session-based MAC Protocol

In this section, we present a new MAC protocol that implements the optimal multicast scheme discussed in the precious section. A flowchart is presented showing the sequence of events that occur from a node booting up to when a session is complete. We also describe various technical considerations critical to implementing the system, such as the ability to accommodate different DTN routing algorithms.

When nodes boot up (Step 1 of Figure 3), they enter the neighbor discovery phase (Step 2) where they gather neighbor information via RF. We use a simple Medium Access Control (MAC) scheme (Step 3) for the link layer whereby nodes are randomly assigned MAC indices. A node with the largest index becomes the active transmitter. An *active transmitter* is the only radio in transmit mode with all neighbors in receive mode (Steps 4, 5a, 5b). Upon the completion of medium access, the active transmitter enters the pairwise buffer discovery phase (Steps 6a, 6b) where it obtains a list of buffer contents via RF of each neighbor. The buffer M_i of a neighbor i, would consist of messages $m \in M_i$, with $M_i = M_{c,i} \cup M_{r,i}$, where $M_{c,i}$ and $M_{r,i}$ are the sets of created and relayed but not delivered messages respectively. The active transmitter uses this information to build a map of messages (Step 7) which have not been seen by each neighbor.

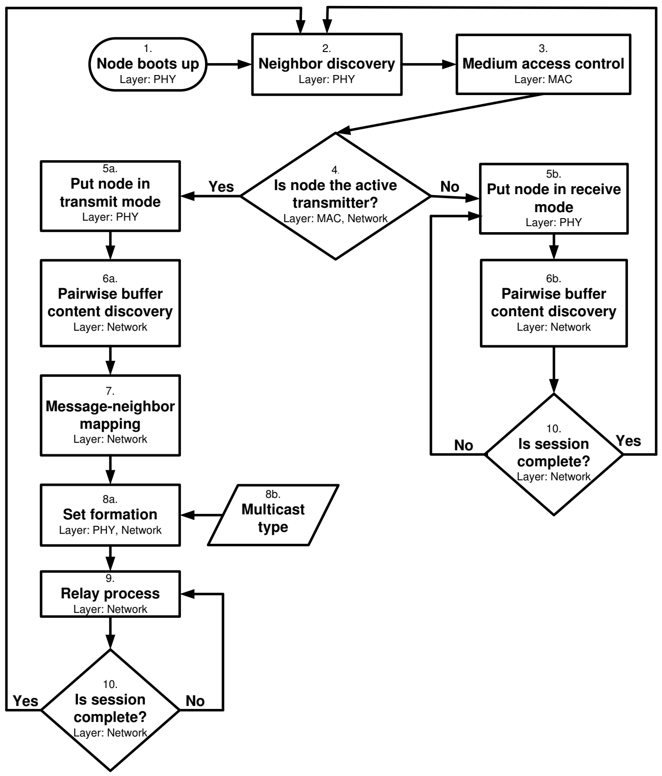

Fig. 3: The system model showing the sequence of events from node boot up to message replication.

Set formation (Step 8) is then performed by the network layer in tandem with the physical layer. With each unique message obtained from the previously discussed mapping, a list of recipients is formed. This list is passed to the physical layer for the computation of sets based on the multicast type (i.e. set cover, FSO broadcast, multiple unicast, heuristic). When the sets have been formed, the physical layer updates the connection speeds of each FSO connection and passes unto the network layer the collection of sets. The active transmitter then proceeds to initiate sessions and relay messages (Step 9). A *session* is defined as consecutive transmissions of a message or a set of messages to a set of nodes. In this work we consider, Epidemic routing [9]. Other routing protocols such as Spray and Wait, Prophet, Rapid and MaxProp can be easily integrated into our work by modifying either the set formation or the relay process. When multicast to a set is complete, and after the realignment period has elapsed, the active node directs its transmitter to the next set of recipients and initiates a new transmission. A session is complete when all nodes in range have a copy of the transmitted message. When a session is complete, a new channel access process begins to elect a new active transmitter, and the entire process repeats (Step 10).

In minimizing both buffer space utilization and overhead, nodes have the capability of sending acknowledgments (ACKs) via RF indicating the final delivery of a sent message. We use first-in-first-out (FIFO) queues for buffer management. To account for the possibility of nodes belonging to multiple quadrants, the divergence angle per set is obtained using

Algorithm 2: Computation of Min. Divergence per Set

Input: Location (x_i, y_i) for nodes n_1 **to** n_N in a set
Output: Minimum divergence angle per set

1 **for** $i \leftarrow 1$ ***to*** N **do**
2     $\phi_i \leftarrow tan(\frac{y_i - y_0}{x_i - x_0})$
3 Sort nodes in clockwise order of ϕ_i to obtain $n_{1'}$ **to** $n_{N'}$
4 $d \leftarrow 1$
5 $\theta_d \leftarrow 0$
6 **for** $i \leftarrow 1^{'}$ ***to*** $N^{'}$ **do**
7   **if** $i^{'} \neq N^{'}$ **then**
8         $\theta_d \leftarrow \theta_d \bigcup \theta(n_{i'}, n_{i+1'})$
9         $d \leftarrow d + 1$
10   **else**
11         $\theta_d \leftarrow \theta_d \bigcup \theta(n_{N'}, n_{1'})$
12 return 2π - max(θ_d)

Algorithm 2. In lines 1 to 3, the sender sorts all receivers in a set using the azimuth ϕ_i relative to the active transmitter. For each pair of adjacent sorted nodes, the divergence angle is found and stored in a vector θ_d (lines 4-11) from which the minimum divergence angle of a set is obtained (line 12). The possibility of having skewed simulation results when a sender and receiver are in each others GPS error range is addressed by using a default divergence angle for such cases.

V. Performance Evaluation

In this section, we analyze results for various schemes: naïve broadcast (FSO BCast) where θ includes all recipients, multiple unicast (MU) which performs N unicasts, our proposed heuristic (Algorithm 1) and the set cover solution (Set Cover).

Simulation Setup:- For the evaluation of the various multicast schemes, we built a simulator in The ONE [18] based on Epidemic routing. The simulation area is 1500 m $\times$ 1000 m with nodes running Reference Point Group Mobility (RPGM) [19]. Nodes move with speeds of 1 - 10 m/s and each group on average consists of four nodes. The simulation is run for 2000 s, with the following traffic generation pattern. In the first 1000 s, a message is created by a randomly chosen source node with a buffer size of 2 TB to a randomly chosen destination, after which a further 1000 s elapses to facilitate message delivery. We evaluate the performance using number of relayed messages, data delivery probability and delay, and throughput as metrics. The simulations are performed using an RF range of 100 m. Each data point is the result of an average of 100 random runs. The parameters we use for the analysis are data size P, GPS error g, alignment delay d_{al}, FSO transmit power P_t, photodetector sensitivity N_b, and number of node groups N_g. The default values (and ranges) used are: P=6 GB (2-10 GB), g=3 m (1-5 m), d_{al}=3 s (1-5 s), P_t=60 mW (20-100 mW), N_b=6 photons/bit (2-10 photons/bit) and N_g=6 (2-10). In addition, we used a wavelength of 1550 nm, a receiver diameter D=12 mm, and 1 Gbps RF control channels.

Relayed Messages:- The number of relayed messages represents the total number of successful transmissions between nodes in the network. In Figure 4, the messages relayed for Set

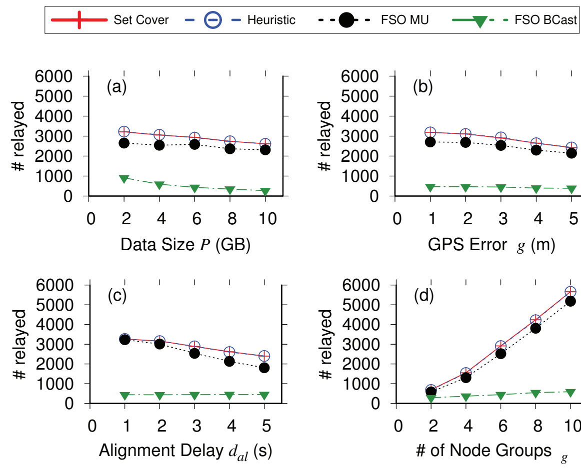

Fig. 4: No. of relayed packets vs. network parameters.(a) Effect of P for P=2-10 GB, (b) Effect of g for g=1-5 m, (c) Effect of d_{al} for d_{al}=1-5 s, (d) Effect of N_g for N_g=2-10.

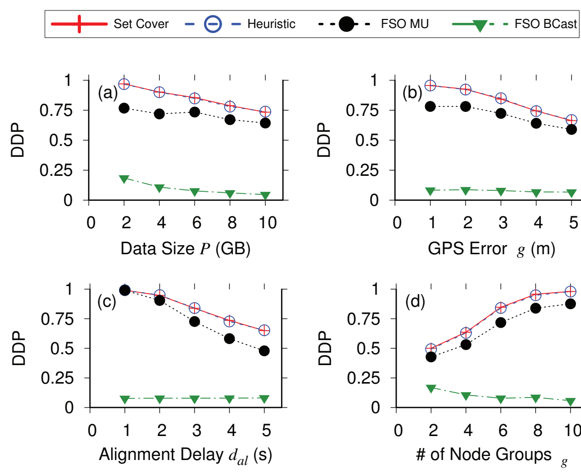

Fig. 5: DDP versus various network parameters.(a) Effect of P for P=2-10 GB, (b) Effect of g for g=1-5 m, (c) Effect of d_{al} for d_{al}=1-5 s, (d) Effect of N_g for N_g=2-10.

Cover and the Heuristic are similar for all parameters. When the number of recipients is low, as it is in the case in DTNs, the heuristic produces a solution close to optimal, since the number of input sets to the set cover solution is considerably low. For FSO MU, the number of relayed packets is less than optimum since it suffers from $(N-1)d_{al}$. FSO BCast has the least number of relayed messages because the transmitter's footprint has to cover all recipients. The θ required to reach all such nodes is large, and R_b decreases significantly, leading to fewer relayed messages.

Data Delivery Probability (DDP):- The data delivery probability (DDP) metric is a measure of the ratio of delivered to created messages. From Figure 5, the Heuristic has a comparable DDP to the optimum (Set Cover), with FSO MU and FSO BCast following in that order. In Figure 5a, for all approaches, DDP decreases as data size P increases. As P increases, the per hop transmission delay increases, resulting in slow replication, hence low DDP. We see in Figure 5b that, a decrease in GPS accuracy (increase in g) results in an increase

Multicast type	$P = 6GB$	$d_{al} = 3s$	$N_g = 8$
Set Cover	702.4	725.6	570.7
Heuristic	706.3	727.8	584.3
FSO MU	865.9	882.5	722.2
FSO BCast	8225.9	7653.5	7260.1

TABLE I: DDD for selected network parameter values. Values for $P = 6GB$ are data points for $P = 6GB$ in Figure 6a, values for $d_{al} = 3s$ are data points for $d_{al} = 3s$ in Figure 6c, values for $N_g = 8$ are data points for $N_g = 8$ in Figure 6d.

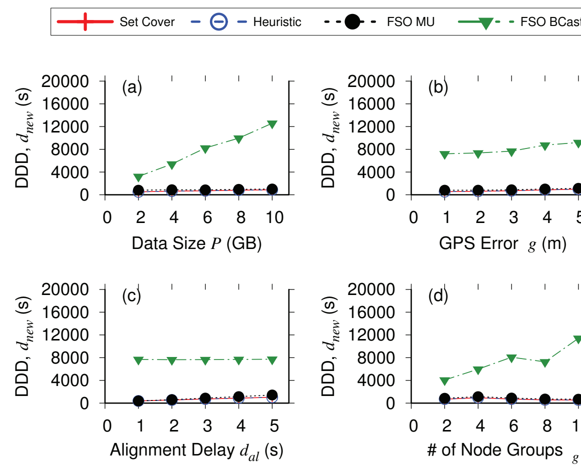

Fig. 6: DDD versus various network parameters.(a) Effect of P for P=2-10 GB, (b) Effect of g for g=1-5 m, (c) Effect of d_{al} for d_{al}=1-5 s, (d) Effect of N_g for N_g=2-10.

in per hop relay delay. This is because, as g increases, the θ required to reach a node while accounting for positioning error increases (i.e., the angle between the two tangents to a circle increases with increasing radius). The greater the θ, the lower the R_b, resulting in an increase in per hop relay delay. The larger the per hop delay, the smaller the message replication, leading to a decrease in DDP. There is a decrease in DDP as alignment delay d_{al} increases (Figure 5c). This is because the data delivery delay is proportional to d_{al}. The result in Figure 5d is particularly interesting. For Set Cover, Heuristic and FSO MU, as the number of node groups N_g increases, DDP increases. For FSO BCast, we observe the opposite: as N_g increases, DDP decreases. An increase in N_g results in an increase in the network density. With Set Cover, Heuristic and FSO MU, these additional nodes serve as extra relay agents which improve replication and subsequently the DDP. With FSO BCast, when nodes are added to the network, the average number of neighbors increases leading to a possible rise in the number of neighboring receivers N. An increase in N & θ leads to a larger per hop delay, resulting in reduced replication & lower DDP.

Data Delivery Delay (DDD):- With sufficient time and buffer space, DTN routing protocols eventually deliver 100 % of created messages. To make our analysis of delay fair across all schemes irrespective of the realized delivery probability, any realistic delay metric has to account for DDP in the estimation of the delivery delay. We define our new DDD metric d_{new} as the estimated time it takes to deliver all created packets. d_{new} is computed using d_{old} (delay reported in ONE)

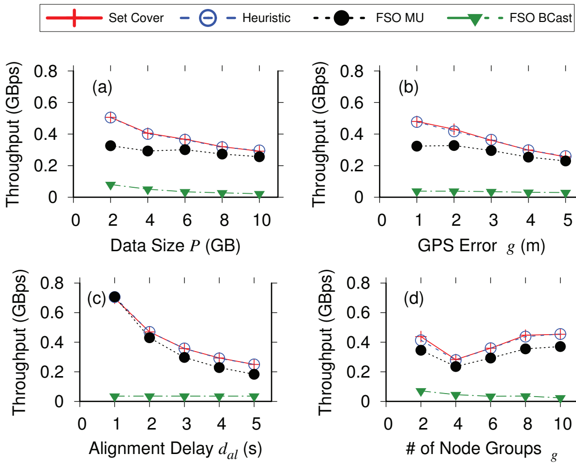

Fig. 7: Throughput versus various network parameters. (a) Effect of P for P=2-10 GB, (b) Effect of g for g=1-5 m, (c) Effect of d_{al} for d_{al}=1-5 s, (d) Effect of N_g for N_g=2-10.

and the DDP and is given as $d_{new} = d_{old}/DDP$. From Figure 6, Set Cover offers the least delay, with the Heuristic following closely as seen in Table I, with FSO MU and FSO BCast in that order. The Heuristic results are identical to that of Set Cover because in sparse networks, the number of receivers is small. There are few receiver combinations $\mathcal{S}$ to pick the optimal cover from. Discovering the optimal $\mathcal{S}'$ is then identical to finding local optimal solutions. In Figure 6a, as P increases, transmission delay per set increases, leading to an increase in delivery delay. The trend in Figure 6b is explained as follows. As g increases, the θ required to reach a node while accounting for positioning error increases, resulting in an increase in DDD. It is obvious that the total delay increases as alignment delay d_{al} increases (Figure 6c). In Figure 6d, for all schemes except FSO BCast, DDD reduces as N_g increases. This is due to the network being denser. From Figure 6, the large FSO BCast delay suppresses the plot of the other schemes. To show how they fare against each other, we include Table I for selected values of some network parameters.

Average Throughput:- We define average throughput to be the total data transferred per unit time taken. In Figure 7, Set Cover and the Heuristic offer the best throughput followed by FSO MU, and FSO BCast. As data size P increases, throughput also decreases (Figure 7a). This is because transmission delay per hop increases with increasing P leading to a decrease in throughput. As GPS error g increases in Figure 7b, the minimum divergence angle θ required to reach all nodes in a set is at least equal to that when g is 1 m. The greater θ is, the greater the per hop transmission delay, hence the reduction in throughput. For all schemes, it is quite obvious that an increase in alignment delay d_{al} (hence total delivery delay) results in a decrease in throughput as shown in Figure 7c. In Figure 7d, for Set Cover, Heuristic and FSO MU, there is a dip in throughput from $N_g = 2$ to $N_g = 4$. With RPGM, when there are just 2 node groups of equal size, the probability of a node in node group 1 N_{g1} creating a message for a node in it's group is 0.5. The message delivery latency is low since these messages are not replicated to nodes in N_{g2} which are likely not in radio range of the transmitter. As N_g increases, the probability of a created message having a destination within the same N_g decreases. Therefore, as $N_g(> 2)$ increases, node density becomes the bigger influence on message replication.

VI. Conclusion & Future Work

In this paper, we showed how to overcome fixed alignment delay in hybrid RF/FSO networks. A new session-based MAC protocol implements an optimal multicast scheme that takes advantage of variable beamwidth. This protocol was integrated into a DTN simulator and evaluated using the Epidemic DTN routing protocol. We are currently working on integrating an online set cover algorithm and variable alignment delay into these networks. This is necessary since in realistic scenarios, discovery of all neighbors might not happen instantaneously. In addition, with accurate multi-receiver PAT, realignments can be performed faster.

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