Performance of DTN-Based Free-Space Optical Networks with Mobility

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***Abstract*—Free-space optical communications (FSOC) has the potential to offer significant capacity advantages for future military communication networks. Due to link fragility, it is likely that FSOC networks will suffer from intermittent connectivity. Delay Tolerant Networking (DTN) has been proposed as a potential solution for this technical challenge as it is designed to offer a solution for routing in a network which is not always connected. This paper examines DTN-based FSOC networks in a variety of mobility models and examines the performance of the network.**

***Index Terms*—Delay Tolerant Networking, Free-Space Optical Communications, Laser Communications**

I. INTRODUCTION

THERE is tremendous increase in overall demand for communications capacity in military missions based on network-centric operations. There is a drive toward network-centric operations which make the communications network critical to an operation through content-rich high-rate products like sensor imagery. In additional there is a lack of available radio frequency spectrum and increasing regulatory pressure with the development of high-rate systems, especially in the commercial domain. Even with efficient use of spectrum (e.g., bandwidth efficiency, demand assignment) the available spectrum is not sufficient, and fundamentally new approaches are necessary. Free-space optical communications (FSOC) has the potential to address both of these challenges. The use of optical bands allows for extremely high capacities, well into the 10's Gbps and beyond. Not only will FSOC operate at bands without regulatory pressure, but it also allows for a high degree of spatial confinement and therefore reuse.

There are many technical challenges in achieving these performance benefits. Pointing, acquisition, and tracking are extremely difficult with long ranges and mobility on rugged terrain. Fog, dust, and atmospheric turbulence are significant impairments for FSOC due to the wavelength and resultant scattering and scintillation of the optical signal. RF/optical hybrids are a likely need for at least mid-term FSOC networks; perhaps for the long-term as well [1-4]. In the case of FSOC, there are also networking design issues resulting from these challenges. First, the FSOC network is an extreme example of the directional antenna mobile ad hoc network (MANET). In FSOC, there is a resultant resource allocation problem having to do with the laser heads. Due to the precision of pointing, these optical heads will need to service just one connection as illustrated in Figure 1. This creates the need for *topology control*. This type of topology control and the natural disruptions of the optical links will result in an intermittently connected network. Delay (or Disruption) Tolerant Networking (DTN) approaches are designed to address networks that exhibit this type of intermittent connectivity [5, 6].

In [7], the authors proposed a DTN algorithm tailored to the directional topology control required with FSOC networks. This algorithm was analyzed in several simple cases and then with one standard mobility model. As with conventional MANETs there is potentially a strong connection between the algorithm's performance and the mobility profile. In this paper, we examine that dependence and determine how well the DTN algorithm performs in several bounding mobility cases. All of these mobility models represent very important military operational environments. These results apply not only to FSOC but to any directional MANET problem using our DTN algorithm.

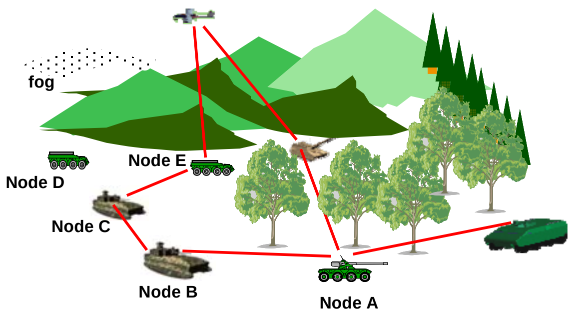

Figure 1. The Tactical Optical MANET

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II. DTN ALGORITHM

We will not provide the full background on our algorithm which can be found in [7] but review the basic approach in this section. We initially make the simplifying assumption that the FSO network nodes have complete information regarding the state of the network including locations of the nodes, the message traffic at each node, and the potential connectivity of network. Given this shared understanding, the nodes perform a joint optimization of link selection and traffic forwarding decisions under the assumption that the connectivity is fragile and can change rapidly compared to the average delivery time for packets in the network (the DTN assumption). In terms of actual implementations, we believe that the RF/optical hybrid fits well with this approach since the RF system can provide the control link to exchange this information at long-range since it is relatively low rate. We also assume that the data exchanges are synchronized according to a known framing schedule. A frame consists of an interval for pointing and tracking followed by an interval for two-way data exchange between nodes and initially we assume that all the messages can be transmitted during a frame.

The algorithm proposed in [7] moves messages toward the destination but we take into account the topology control necessary for the FSOC networks and for that we developed a new metric. Recognizing the intermittent nature of the link, we desire that the FSOC network move information closer to its destination but allow a period of time (hops) for the information to reach its destination. We must include a mechanism to make the choices about how to allocate optical heads in the control of the topology.

We first define a key metric which will be needed for the algorithm. We define the *transient information level* (*TIL*) of the network as the product of the information (units of messages) and the projected physical distance of that information from its destination node. The goal of the algorithm is to minimize the *TIL* across the network taking into account the FSOC constraints. When all message have been delivered to their destinations, $TIL=0$.

We first introduce the formal mathematical representation of the algorithm and then show a simple example. We assume a homogenous network of N nodes. We assume that the nodes have location knowledge across the network and construct an NxN symmetric matrix, D, in which element $D(i,j)$ is the physical distance between nodes i and j. For a given frame, the matrix T represents the traffic in the network, with $T(n,m)$ denoting the amount of traffic at node n to be delivered to node m. Since this is a DTN approach, the node at which this information resides is not necessarily the source node but the current custodian of the messages. The network chooses a set of FSOC links to activate during that frame, and the nodes decide which messages to forward over the activated links based on whether that information would be closer to its destination if it is moved along that link. We represent this decision by saying that node n moves messages $T(n,m)$ to node $h(n,m)$. If the traffic $T(n,m)$ is retained by node n, then $h(n,m)=n$. Note that entries in T can include new traffic that is generated during each frame.

The active links representing pointing of the FSOC beams are then determined by the NxN pointing matrix P where the (i,j)th element is 1 if a FSOC beam exists between nodes i and j, and 0 otherwise. Given that both the transmitter and receiver must allocate an optical head for communications, P is symmetric. Recall that it may not be feasible to point the beam based on distance, blockage or other factors. Therefore we represent feasible connectivity by the NxN matrix C where elements are 1 if connectivity is possible and 0 otherwise. Assuming that each node has p_{max} transceiver resources (optical heads) to allocate, we have the constraint that the pointing matrix P be symmetric and have row weight and column weight at most p_{max}.

Given the mathematical terms we now can present the algorithm. We seek to find P which minimizes

$$TIL=\sum_i \sum_j D(h(i,j),j)\,T(i,j)$$

at the next frame. Selection of P is constrained by the possibility of a connection provided in C and itself dictates the transfer of movement provided in h based on the residual distance criterion, a function of D.

III. MOBILITY MODELS

We focus this paper on three mobility models which represent a range of environments to stress the algorithm. A primary motivation to examine the performance is due to some pathological cases which we reported in [7]. Since the proposed metric may be regarded as an “energy”-like quantity that the network should naturally seek to minimize. Despite the appeal of this intuition, there are interesting limitations to the approach. In particular, there are static network configurations that are pathological with respect to the TIL metric. Consider, for example, a semi-ring network in Figure 2 which the two end nodes A and Z are unable to communicate directly due to distance or blockage but are able to communicate in the “wrong direction” around the undamaged part of the ring. Using the TIL metric, node A will never release custody of messages intended for node Z since the only path available (through B) initially increases “energy” in the system. Successful forwarding of messages from A to Z would require that the TIL “energy” continue to increase until the messages arrive at node A*. From node A*, minimization of TIL would begin to push the messages in the proper direction. Similar results apply to traffic for node A from nodes Z and Z*. Clearly, this example can be made arbitrarily bad by adding additional nodes in the “backwards” direction.

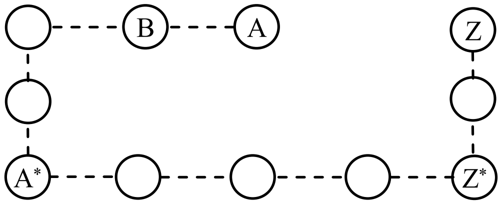

Figure 2. Pathological Case for TIL

Since we are focused on mobile networks, it is not clear how much of a problem these cases are since they are static. As reported in [7] we found via a preliminary example of how the algorithm worked in one mobility model however we want to understand its performance more fully. Therefore we assess the performance of our DTN algorithm with three models. The first model, Random Waypoint, is a standard for MANET evaluation as can be found in [8]. The Rendezvous Model is a new model described fully in [9]. Finally we implement a Manhattan Model which is motivated from general discussions in the literature [8].

A. *Random Waypoint Model*

The Random Waypoint model was established in the MANET community to test various algorithms like routing. In this model a random location in an operating region is determined and the node will move to that location at a randomly chosen velocity. In our model we use a uniform random velocity chosen between two velocities that are inputs to the model. In addition, the Random Waypoint Model includes a parameter which controls a pause of the nodes after they reach their destination.

B. *Rendezvous Model*

In [9], the authors propose a classification of mobility models into goal-oriented and non-goal-oriented approaches. They further develop a general schema for Goal-Oriented Mobility Models and show how the prior goal-oriented models such as the Random Waypoint Model fit the schema. Based on the general schema, they develop a new goal-oriented mobility model, called the Rendezvous Model that differs from prior mobility models in its strategy for assigning nodes to goals. The Rendezvous Model provides a simple abstract model for ad-hoc tasking that should be of practical interest in both civilian and military networking applications.

In the Rendezvous Model, there are N nodes and G goals with G < N. The goals are destinations that are randomly selected as in the Random Waypoint Model. Like the Random Waypoint Model, the nodes move towards the goals at randomly selected speeds. Unlike the Random Waypoint Model, the nodes are randomly assigned to goals; and, when a node arrives within a specified range of its assigned goal, it stops and waits for a rendezvous with other nodes assigned to the same goal. A rendezvous occurs when two or more nodes arrive at their shared common goal. Once a prescribed number of rendezvous occur, the nodes are randomly reassigned to different goals and the goals are randomly repositioned.

The strategy of reassigning the nodes after completion of goals leads to the formation of teams on an ad-hoc rather than permanent basis. Thus, the Rendezvous Model is a group mobility model with more structure to the nodes' trajectories than in the Random Waypoint Model. The trajectories are spatially and temporally correlated since nodes tend to move closer together over time in order to rendezvous. But the structure is quite different compared to that of other group versions of the Random Waypoint Model, which have local structure due to permanent teams assigned to a common team goal. In the Rendezvous Model, there is no persistent spatially coherent local structure since the teams disperse in a random fashion after rendezvous. See [9] for a more detailed discussion of the Rendezvous Model and its variations.

C. *Manhattan Model*

The Manhattan Model is implemented to evaluate performance of the network in urban environments. One major constraint of FSOC is the need for line of sight (LOS). Thus FSOC could be significantly limited in an urban environment due to blockage. Our model is 10x10 city blocks which results in 11 streets horizontally and 11 vertically. The nodes begin at random locations located at an intersection. A movement direction is selected both horizontally and vertically with equal probability. A value for a counter is selected for the horizontal and vertical travel time. The node will move vertically if there is a greater remaining vertical travel time and horizontal otherwise. These are obviously subject to the constraints that the node must be at an intersection switch directions. When the counters reach zero, new horizontal and vertical directions for movement is randomly selected. A trace of three nodes moving through the city blocks is shown in Figure 3.

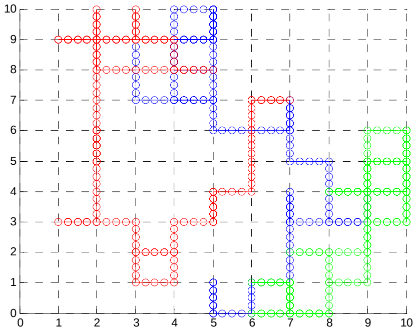

Figure 3. Three Nodes in Manhattan Mobility

IV. SIMULATION RESULTS

We have implemented the TIL routing in simulation to study its effectiveness in dynamic test scenarios. In these test scenarios, each node has one message to send to every other node, and the metric of interest is the time it takes to reduce TIL to zero which we sometimes refer as “draining TIL”.

For the Random Waypoint and Rendezvous models connection probability for any given pair of nodes varies inversely with the squared distance between them. Figure 4 shows the performance effects of node velocity in the 5-node network with 4 heads per node. Figure 4 shows three different speeds (velocity doubled from slow to moderate and doubled again from moderate to fast) in the waypoint model. We see a marked improvement from slow to moderate but diminished improvement as speed again doubles.

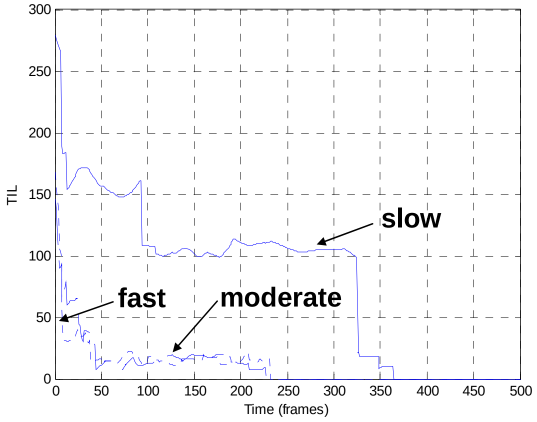

Figure 4. Performance with Various Speeds

One of the parameters of the Random Waypoint model is pause time, as described earlier. We expect that the network would exhibit a slower TIL drain with greater pause values. Figure 5 shows four simulation runs in which pause was doubled from one run to the next. As expected, the longest pause (a factor of eight greater than the shortest) showed a much longer draining time.

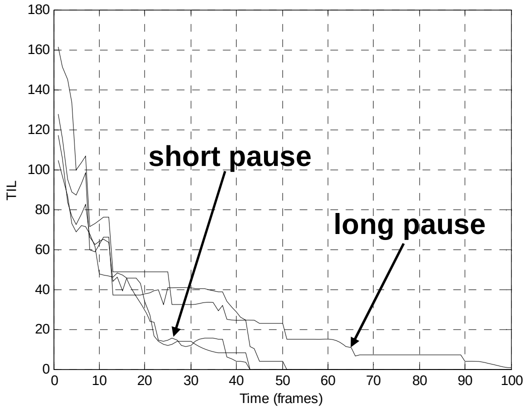

Figure 5. Effect of Random Waypoint Pause

Though four heads are available on the nodes it turns out that only two heads are utilized by any node in the scenario as shown by Figure 6. This is due to the relatively spare connectivity of the 5 nodes randomly moving about the operating region. In many scenarios, such as operational military units, the units will not be spread randomly but rather would cluster in various ways. In order to examine this performance we next show the Rendezvous mobility performance, particularly relative to the Random Waypoint.

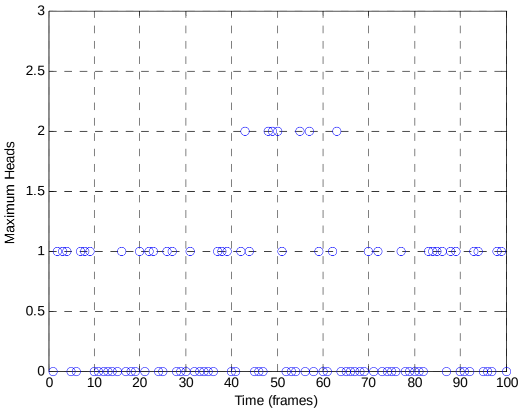

Figure 6. Maximum Number of Optical Heads Utilized

The Rendezvous Model has a rich set of parameters with which to exercise the DTN protocol. A full discussion of this range of performance can be found in [9]. In this case, the algorithm was run with 10 nodes and 5 goals per game with one goal required to move to the next game. The speeds, number of nodes, and number of heads were matched to those of a Random Waypoint model. Nodes were started in the same location to ensure the TIL started at the same value. The pause in the Random Waypoint was set at a relatively low value. These were run with three heads. Figure 7 shows the side-by-side performance comparison. The Rendezvous model shows a more rapid drain of TIL from the network. This is due to the proximity of the nodes which tend to cluster more than in the Random Waypoint model. We illustrate this with Figure 8 which shows a histogram of the number of heads used in each case. In this case all aspects of the simulation are the same except proximity from the mobility models, thus the number of heads used will increase as nodes are more closely located.

Finally, we exercise the algorithm through the Manhattan mobility model. Since it is not a goal-oriented mobility model we do not assess it against the Random Waypoint and Rendezvous models. For the illustration of TIL features due to the obstructions in this urban model, we initially assume an infinite range of communications. Figure 9 shows the performance of TIL drainage in a case of the Manhattan model with a 10-node network with 3 heads per node. As noted from the figure, the performance in this cases exhibits discrete “step function” type drops in TIL which occur as nodes reach intersections simultaneously with others and transmit. The figure shows a dramatic drop in TIL at frame 32. Figure 10 shows the location of nodes at this frame and the subsequent pairing of communications. Nodes 6 and 10 are coincident at an intersection. As noted, there is very significant connectivity achieved at this point and thus TIL drops dramatically.

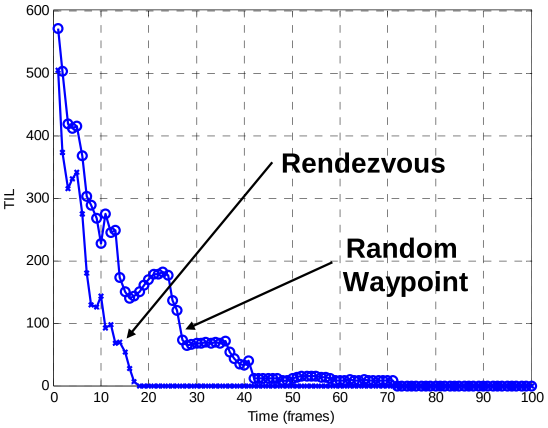

Figure 7. Performance Comparison of Rendezvous and Random Waypoint

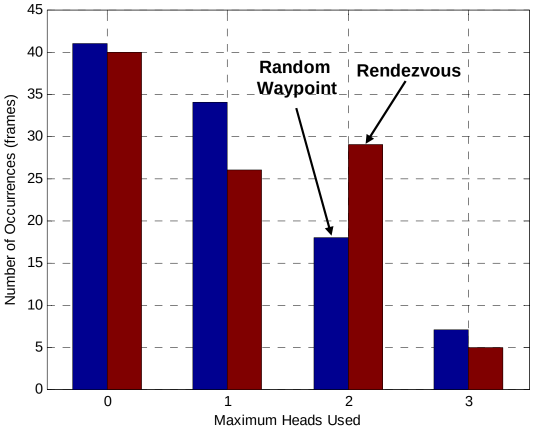

Figure 8. Comparison of Head Utilization

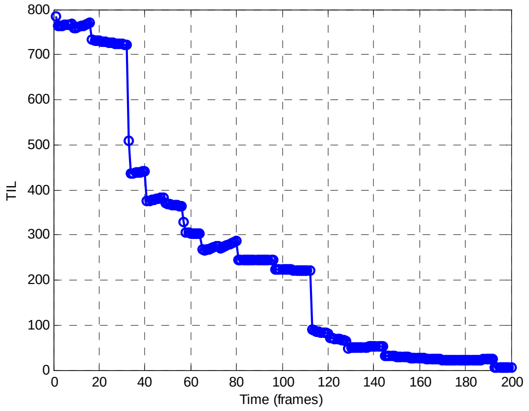

Figure 9. Performance with Manhattan Model

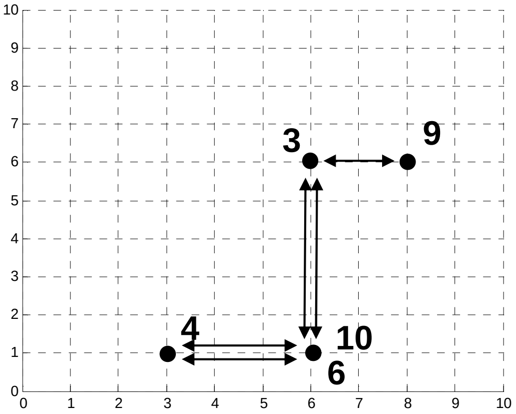

Figure 10. Locations at Frame 32

We next investigate the impact of nodal velocity on the performance of the network as shown in Figure 11. In this case, we double the speed for each new run, thus the simulation run labeled ‘fast’ has nodes moving eight times as fast as the ‘slow’ run. The features of the sharp edges are not pronounced in the higher speed cases since communications opportunities at intersections are occurring much more frequently.

The last simulation case shown in Figure 12 we consider multiple communications ranges assuming that the nodes can only communicate an integer number of streets ranging from a single street to the unlimited case. There is little performance impact from the unbounded case down to a 5-street range. Communications opportunities are more limited with the smaller ranges and with a 1-street range it is noted that the messages are held by nodes for a considerable period before finally reaching the destination.

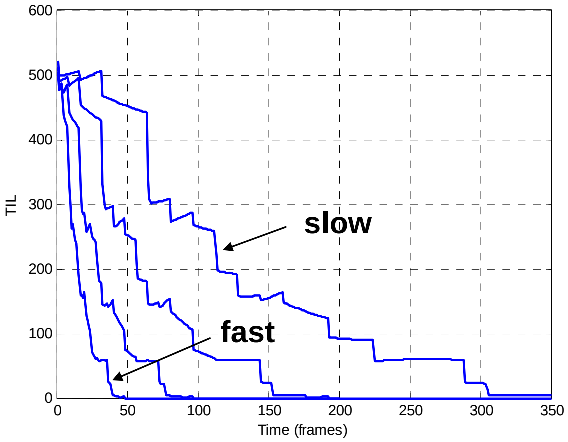

Figure 11. Effect of Velocity in Manhattan Mobility

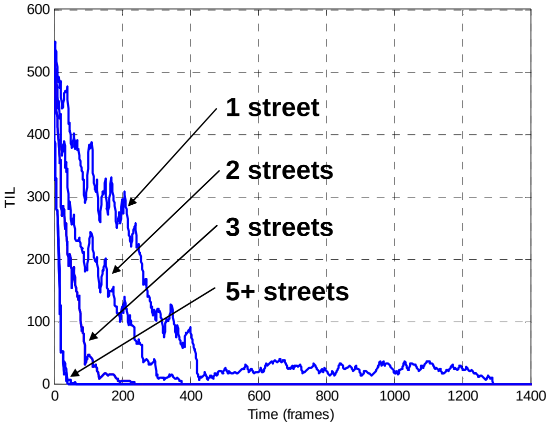

Figure 12. Effect of Propagation Distance in Manhattan Mobility

V. SUMMARY

We have proposed a DTN algorithm for FSOC and in this paper have exercised the algorithm in three mobility models which have considerably different features. All are relevant to military communications scenarios. We have illustrated performance by considering the "draining" of a network's TIL. The DTN algorithm appears to be very robust under a range of mobility conditions in all three models, from speed to propagation distance.

This algorithm is not restricted to FSOC but could be applied to any directional MANET. It would be beneficial as a subsequent effort to use high fidelity models of a particular system and environment in RF, some of which are emerging, and examine performance of the DTN approach.

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