Performance Comparison of Unicast Routing Schemes in DTNs

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Abstract—**Delay and disruption tolerant networks have been proposed to address data communication challenges in network scenarios where an instantaneous end-to-end path between a source and destination may not exist, and the links between nodes may be opportunistic, predictably connectable, or periodically-(dis)connected. In this paper, we focus on comparing the performance of different unicast routing schemes proposed for intragroup communications. In particular, we conduct performance studies for different DTN scenarios, e.g., DTNs with different node densities, DTNs with different mobility models, networks with different percentage of nodes supporting DTN functionality, etc. In addition, we also study intergroup DTN routing scenarios where message ferries and backhaul links are used. Our results indicate that (a) the store-and-forward and custody transfer concepts have significantly improved the delivery ratio in a sparsely connected network, (b) in very sparse networks, message ferries are required to enable communications, (c) a high delivery ratio can be maintained even with only 50% of the nodes supporting DTN functionality, (d) the two-way delay in bidirectional flows only experience 10% more delay than one-way delay, and, (e) some routing schemes are optimized to perform well in certain mobility scenarios and thus a hybrid scheme will work best in all scenarios.**

Keywords-disruption tolerant networks; custody transfer; route discovery; message ferry

I. INTRODUCTION

Packet-switched network communication has been studied for decades. Important progress has been made in robustness and scalability in the TCP/IP protocol suite based primarily on principles of end-to-end protocols and services [9]. However, there are many scenarios in which an end-to-end connection is not guaranteed or even possible, and so an intermediary is needed, perhaps to translate between protocols or to provide temporary storage (e.g., in mail servers). In these cases, without such intermediaries, communication would fail. In other cases, communication may fail not because of a lack of instantaneous connection, but because the connection properties fall beyond the expected bounds (excessive round-trip-time or high packet loss probability).

Solutions have been proposed to deal with some specific situations, e.g., using link layer retransmissions to deal with high packet loss probability in wireless environments [4] or using performance enhancing proxies [28]. However, these solutions still do not work in situations where there are no end-to-end paths. In contrast, DakNet [3] deploys physical transport devices, e.g., buses and motorcycles, to carry mobile access points between village kiosks and hubs with Internet connectivity so that the data carried by the physical transport devices can be automatically uploaded and/or downloaded when the physical transport devices are in the wireless communication range of a kiosk or a hub. Similar techniques are proposed in [1],[2]. In the past two years, a considerable amount of research focusing on delay/disruption-tolerant networking and communications has been published (e.g., [13],[14],[15],[27]). DieselNet [14],[27] is a disruption tolerant network where connections between nodes are short-lived and occasional. A common approach used to address delays and disruptions is via the use of a store-and-forward mechanism similar to electronic mail [11]. This makes communication possible, even when an instantaneous end-to-end path does not exist. Message ferrying schemes [14],[27] are proposed where special mobile nodes called message ferries are used to facilitate connectivity between nodes. The message ferries visit the nodes in the network and deliver data among them.

In [5], Fall describes an architecture for delay tolerant networking that implements much of what we have described. It proposed the idea of topological regions connected by gateways, which were responsible for storing messages in non-volatile storage to provide for reliable delivery. End-point addressing in his scenario consisted of a region name used for inter-region routing and a locally-resolvable name for intra-region delivery. More recently, we have proposed an enhanced disruption-tolerant network architecture called EDIFY (Enhanced Disruption and Fault Tolerant Bundle Delivery) [6]. Our approach builds on many ideas from Fall, but adds support for multiple, overlapping name spaces and node and group mobility.

In this paper, we focus on comparing the performance of different DTN unicast routing schemes. Specifically, our contributions in this paper are:

(a) we study the effectiveness of the custody transfer feature with on-demand routing protocols in DTNs. It is important to know when the custody transfer feature needs to be turned on since the deployment of the custody transfer feature incurs extra overhead.

(b) we study the impact of mobility models on the performance of on-demand routing protocols in DTNs. We consider both the random waypoint model and the Zebranet-like model.

(c) we compare the performance of two-hop [19], and multihop routing schemes in DTNs. We believe this is the first paper that compares the performance difference between the two-hop and multihop routing schemes in DTNs.

The rest of our paper is organized as follows: we first give an overview of the three routing approaches that have been proposed for forwarding intragroup messages in DTNs in Section II, and discuss their advantages and disadvantages. In Section III, we study the performance of intragroup message delivery by studying the impact of node densities and mobility models on intragroup message delivery ratio. In addition, we also compare the performance of 2-hop and multihop unicast routing approaches in DTNs. Our results indicate that a multihop unicast routing approach can provide higher delivery ratio and lower packet delivery latency. Next, we describe how routes for intergroup communications can be discovered. In Section V, we study the performance of intergroup communications in a DTN with message ferries and backhaul links. Our results indicate that the presence of message ferries and backhaul links allow otherwise partitioned groups of nodes to communicate with one another. With appropriate buffer size, the delivery ratio for intergroup messages can be maintained at more than 83%. We give some concluding remarks in Section VI.

II. INTRAGROUP ROUTING SCHEMES FOR DTNS

Three categories of forwarding schemes have been proposed for DTNs. In the first category [20], message ferries or data mules are proposed to gather data from stationary sources and deliver them to their destinations. However, for nodes that move, they can be message carriers themselves without having to resort to special message ferries. In the second category [21],[22], history-based routing is proposed in which each node maintains a utility value for every other node in the network, based on a timer indicating the time elapsed since the two nodes last encountered each other. These utility values, which carry indirect information about relative node locations, get diffused through nodes' mobility. Nodes forward message copies only to those nodes with a higher utility for the message's destination. For example in [22], the authors propose a probabilistic metric called delivery predictability at every node A for each known destination B. This metric indicates how likely it is that node A will be able to deliver a message to that destination. The delivery predictability ages with time and also has a transitive property, i.e., a node A that encounters node B which encounters node C allows node A to update its delivery predictability to node C based on its (A's) delivery predictability to node B and node B's delivery predictability to node C. In [22], a node will forward a message to another node it encounters if that node has higher delivery predictability to the destination than itself. Such a scheme was shown to produce superior performance than epidemic routing [25]. We anticipate that the transmission overhead (defined as the number of transmitted bytes over the number of generated bytes) for such schemes will be similar to that achieved using a routing protocol combined with custody transfer (about which we will elaborate below). The results in [22] (Figure 3 in [22]) suggest that the transmission overhead will be close to 35.6% (with a transmission range of 100 m and using the random waypoint mobility model) for the case with 200 buffers.

In the third category [19], [23], a two-hop relay forwarding scheme is proposed in which the source sends multiple copies (e.g., different erasure coding blocks) to different relaying nodes and the relaying nodes deliver the copies they have to the destination node when they encounter the destination node. Again, such a strategy will achieve small transmission overhead but may not enjoy high delivery ratio for messages with shorter deadlines.

A. *Custody Transfer Feature*

In our work, we assume support for custody transfer is turned on in some DTN routing schemes. This custody transfer feature is proposed in [13],[17] to provide reliable communications in an intermittently connected network. In this scheme, accepting a message with custody transfer amounts to promising not to delete it until it can be reliably delivered to another node providing custody transfer or it arrives at the destination. Nodes holding a message with custody are called custodians. Normally, a message has a single custodian (referred to as sole custody) but in some circumstances, more than one custodian owns a message or message fragment (referred to as joint custody). Applications can optionally request the custody transfer feature on a per-message basis and they will receive a custody acknowledgement when their host system can find one or more nodes that are willing to take custody of the message. A node may agree to accept custody for messages initially and refuse to do so when its local node resources, e.g., buffers, become substantially consumed. Potential problems that may occur with custody transfer are discussed in [17].

The custody transfer feature considered in this paper works as follows: when a DTN node has a message to send for which it holds custodianship, it checks its cache to see if it has a route to the destination node. If it finds more than one route, it picks the one with the lowest cost (e.g., using hop count, delivery latency etc., as metrics). When a route is selected, it checks the DTN nodes included in this selected route to see which node is the best candidate for custody transfer, e.g., the closest DTN node that has buffer space available. Then, it sends a custodian request to that downstream DTN node. If the DTN node can accept the custodianship, it will respond with a custody acknowledgement. Otherwise, it sends a negative reply.

If the sending DTN node cannot find a route to the destination of the message, it will send a custody request to its 1-hop DTN neighbors to see if any one of them has a route to this destination. If there is a custodian accept reply from any 1-hop DTN neighbors, then, this sending DTN node will send the bundle to that replying node. If there is no reply (after a wait-for-reply timer expires), then this sending DTN node will trigger its underlying ad hoc network layer to look for a route or neighboring nodes that are closer to the destination than itself. At the ad hoc network routing layer, all DTN nodes that receive a route reply message with the DTN option flag set will set a bit in the appropriate position (according to its hop distance from the sending node of the route request) to indicate buffer availability before relaying the route reply message. Thus, our dual-layer (at ad hoc network routing and DTN layers) approach allows a node to identify downstream nodes to which we can forward the messages. Once a custodian node is selected, the sender transmits a message to it and waits for an acknowledgement. If the sender does not receive custodian acknowledgement from the new custodian node, it will retransmit up to a certain maximum number of times. If the sender still fails to receive acknowledgement after multiple attempts, the sender can select another node to be the custodian. Our custody transfer implementation avoids the head of line blocking problem described in [17] by allowing the DTN node to search through the queued messages until it finds a message that can be sent to the next hop node.

III. PERFORMANCE STUDY OF INTRAGROUP COMMUNICATIONS

A. *Impact of Node Densities in a DTN with Custody Transfer*

In this section, we investigate how the presence of DTN nodes supporting custody transfer in a sparsely connected ad hoc network impacts the system performance. DSR-like routing [18] is used as the default routing protocol. The delivery ratio of such a multihop routing approach is expected to degrade with increasing network sparseness even with the custody transfer turned on. We conducted two sets of experiments. We simulate a scenario where there are 40 nodes. The 40 nodes are distributed randomly in the following areas: (a) 1000x1000 m^2, (b) 1500x1500 m^2, and (c) 2000x2000 m^2. First, we run some experiments assuming that the nodes do not support custody transfer, i.e., they are just regular adhoc network nodes. Then, we run the same experiments assuming all nodes turn on the custody transfer feature.

10 source/destination pairs are used in this set of experiments. The source/destination pairs are randomly picked among the 40 nodes. Each source generates one packet every 4 seconds. The packet size is 512 bytes. The nodes move according to the random waypoint model with a maximum speed of

5 m/s. Table 1 shows the results we obtained without custody transfer and Table 2 shows the results we obtained when custody transfer feature is turned on. The performance metrics we use are:

(a) transmission overhead [19] which is defined as the number of transmitted bytes over the number of generated bytes. Note that in this case, the transmitted bytes include the routing overhead. Each routing message and each custody transfer request/acknowledgement message is assumed to be 35 bytes long.

(b) total number of control messages sent (including custody transfer acknowledgements)

(c) the average end-to-end delivery latency (denoted as Avg Delay in the tables)

(d) the packet delivery ratio (PDR), and,

(e) the average hop counts of the chosen path.

For each scenario, we conduct 10 simulation runs and report the average of the metrics obtained from these 10 runs. From Table 1, we see that the packet delivery ratio starts to drop significantly (by 19%) when the node density changes from [$1x10^{-5}$ /m^2 to $4.0x10^{-5}$ /m^2 assuming that the transmission range is 250 m. The drop in PDR is 30% as the node density decreases from $1.8x10^{-5}$ /m^2 to $1.0x10^{-5}$ /m^2. Table 2 shows how the custody transfer feature significantly improves the packet delivery ratio for those scenarios where the node density is below $1.8x10^{-5}$ /m^2. In the 2000x2000 m^2 case, we see that the delivery ratio has dropped to 48% without custody transfer. However, the packet delivery ratio increases to 98.6% when the custody transfer feature is turned on. The additional price to pay for this improvement is an increase of transmission overhead by almost 217%(=(10.49-3.27)/3.27) and an increase of 117% (=(113762-52396)/52396) in control overhead for the case with a node density of $4x10^{-6}$/m^2. We expect the delivery ratio to drop significantly when node density continues to drop and the custody transfer feature alone will not be enough to allow the sparsely connected nodes to communicate with one another. We propose to use message ferries in very sparse ad hoc networks and will elaborate on the benefits of using message ferries in Section V.

Table 1: Without Custody Transfer

Node Density	Total # of control messages	Total # of data messages	Transmitted bytes over generated bytes	Avg delay	Delivery Ratio	Avg Hop count
$4.0x10^{-5}$	223391	6131	9.54	0.57	97.1%	3.87
$1.8x10^{-5}$	126035	7346	7.03	3.69	78.0%	5.24
$1.0x10^{-5}$	52396	3870	3.27	6.54	48.0%	4.64

Table 2: With Custody Transfer

Node Density	Total # of control messages	Total # of data messages	Transmitted bytes over generated bytes	Avg delay (sec)	Delivery Ratio	Avg Hop count
$4.0x10^{-5}$	229645	7376	10.49	1.59	100%	3.9
$1.8x10^{-5}$	158688	18091	13.16	43.4	99.9%	5.7
$1.0x10^{-5}$	113762	15098	10.39	259.4	98.6%	5.25

B. *Impact of different mobility models*

In this section, we describe an experiment we conducted to understand the impact of mobility models on the system performance. In this experiment, we simulate a scenario where 34 nodes are randomly distributed over an area of 1500mx1500m and the nodes move either according to random waypoint model or according to Zebranet movement [19]. For the random waypoint movement, the nodes have a maximum speed of 5m/s. For the Zebranet movement, we scale the node positions to be within 1500mx1500m area. To maintain similar node connectivities, we reduce the transmission range to 250 m (as compared to 1000 m in the original simulation reported in [19]). In the original Zebranet trace [19], the inter-sample interval is 8 minutes but we scale this interval to 8 seconds in the experiment we conducted. This means that in our experiment, the nodes move faster than those reported in the original Zebranet trace. Table 3 tabulates our results. The faster and more chaotic node movements that are based on the Zebranet trace result in higher average packet delivery latency (30.6 seconds compared to 22.6 seconds). The transmission overhead is also higher using the Zebranet mobility model as compared to that obtained using random waypoint mobility model.

Table 3(a): System Performance with ZebraNet Movement

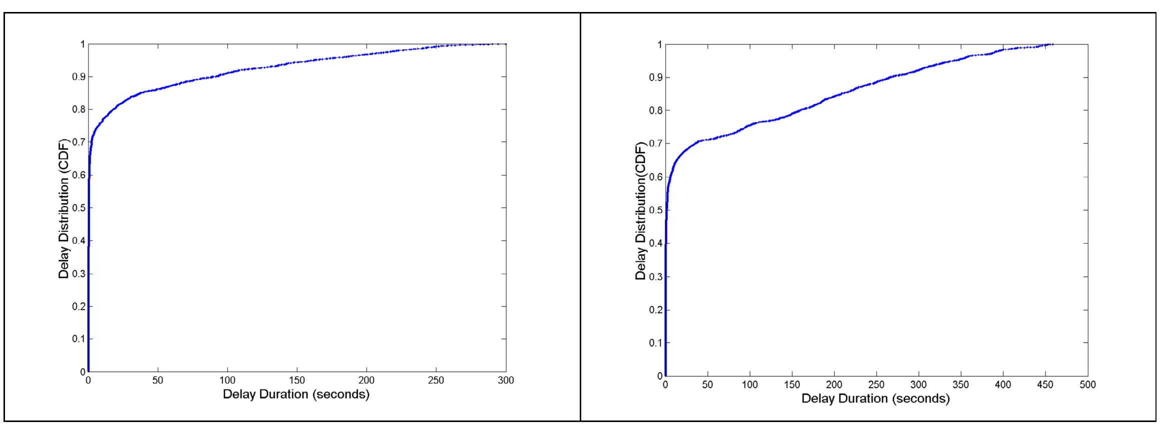
	Total # of control messages	Total # of data messages	Transmission Overhead	Avg delay (sec)	Delivery Ratio	Avg Hop count
RWP(5m/s)	145594	13014	10.45	22.6	99.9%	4.78
Zebra	129653	16521	11.23	30.6	99.9%	4.56

We conducted another experiment where we scaled all the reported distances by 4 (to fit the locations to within the 1500mx1500m rather than the 6000mx6000m as described in [19] and scaled the time unit such that the nodes will be moving at the same speed as reported in [19]). The result is tabulated below. We see that when the nodes move slower using the Zebranet mobility model, the average packet delivery latency and transmission overhead increases. The packet delivery latency increases from 30.6 seconds to 68 seconds while the transmission overhead increases from 11.2 to 15.1.

Table 3(b) System Performance with another Zebranet mobility model

	Total # of control messages	Total # of data messages	Transmission Overhead	Avg delay (sec)	Delivery Ratio	Avg Hop count
With custody transfer	169595	23301	15.14	68	99.9%	5.98

The delay distributions obtained using the random waypoint model and using the Zebranet model are plotted in Figures 1(a) and 1(b) respectively. Here, we see that the Zebranet mobility model results in packet delivery latency that has a higher tail. The 90 percentile delay is 100 seconds using the random waypoint model but it is 260 seconds using the Zebranet model. If we translate the time unit from minutes to seconds in [19], the 90 percentile packet delivery latency achieved using the 2-hop relay forwarding scheme as reported in [19] is close to 1200 seconds. Thus, we anticipate that the packet delivery latency will be smaller with the multihop routing approach as compared to the 2-hop relay approach. More simulation studies comparing these two forwarding schemes will be discussed in subsection E.



(a) Using RWP (b) Using Zebranet model

Figure 1: Delay Distribution using different mobility models.

C. Impact of DTN percentage & bidirectional flows

In this section, we investigate how the percentage of DTN nodes impacts the delivery ratio. We also measure the end-to-end delay for bidirectional flows. In this set of experiments, we simulate 40 nodes randomly distributed in an area of 1000x1000 m^2. The nodes move according to the random waypoint mobility model. In addition, we select 10 source/destination pairs that require many hops for packet delivery. Bidirectional flows are implemented as follows: a source sends a message to a destination and the destination will respond with a message of the same size back to the source before the source generates further messages. Then, we evaluate the delivery ratio, the one-way end-to-end delay, the two-way end-to-end delay as well as the transmission overhead. The results for 50% DTN nodes and 100% DTN nodes are tabulated in Table 4. The delay distributions for both cases are plotted in Figures 2 & 3 respectively.

	100% DTN	50% DTN
Delivery Ratio	98.7%	96.5
Avg One-way Dly (sec)	278	257
Avg Bidirectional Dly(sec)	316	284
Transmission Overhead	13.1	11.0

Table 4: Impact of DTN percentage

From the results, we see that even with 50% DTN nodes, the delivery ratio is as high as 96.5% and the one way and bidirectional delay is reasonably low. The 95% one-way delay is about 1150(927) seconds and the 95% bidirectional delay is about 1650 (1250) seconds for the 100% (50%) DTN nodes case. Those packets that are not delivered in the 50% DTN nodes case but are delivered in the 100% DTN nodes incur larger delay. Thus, we observe larger 95% bidirectional delay for the 100% DTN nodes case when compared to that achieved in the 50% DTN nodes case.

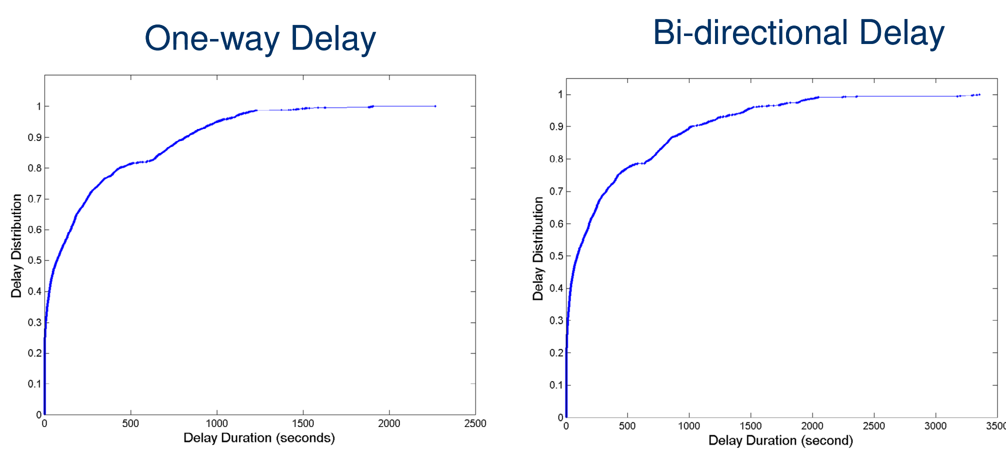


Figure 2: Delay distribution for 100% DTN nodes case.

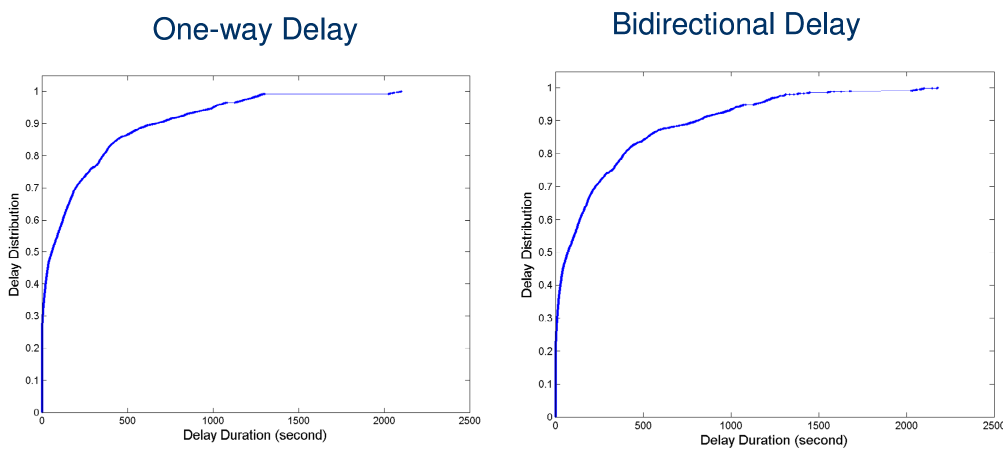


Figure 3: Delay distribution for 50% DTN nodes case.

D. Impact with varying link bandwidths

The DieselNet [27] trace does not have accurate GPS information. Thus, we cannot use the trace data to provide yet another mobility model. However, the trace provides information about varying link bandwidths between two nodes. Figure 4 shows the CDF of the link bandwidths information we extracted from the trace. We fit this data to a Pareto distribution and use this distribution in our simulator. The CDF of the fitted Pareto distribution is as shown in Eq 1 below.

$$F(x) = 1 - \left(\frac{3}{3 + \frac{x}{100}}\right)^5 \qquad \text{--- (1)}$$

In the first set of experiments, we use 40 nodes distributed over an area of 2000x2000m^2. When a node needs to send a packet to another node, we assume that the available link bandwidth is obtained from this distribution. We vary the traffic load from 0.25 pkt/sec to 1 pkt/sec. The nodes move according to random waypoint mobility model with a maximum speed of 5 m/s. In this first set of experiment, the buffer size is set to 1200 messages. Table 5 tabulates the results we obtained. In Table 5, the results using the varying link bandwidth are labeled as UMASS trace and the results using fixed bandwidth are labeled as RWP. The varying link bandwidth (varies between 0 to 2 Mbps) increases the average packet delay. From Table 5, one can see that providing a buffer size of 1200 messages is sufficient to maintain delivery ratio at 97-99% at all traffic load (up to 1 pkt/sec).

Since the buses in [27] move rather fast, we also conducted another set of experiments where the nodes move with a maximum speed of 20 m/s. Each node's buffer size is still set at 1200 messages. The results for this second set of experiments are tabulated in Table 6. We observe that the delivery ratio can still be maintained at high values. The average delay has increased since the links get broken more easily at higher speed, and hence the packets incur additional route repair and route re-discovery delays. The difference in the achieved delay with varying link bandwidth and with fixed bandwidth is more significant in the fast moving scenario (Table 6) than the slow moving scenario (Table 5). The bigger difference can be attributed to the fact that more messages need to be retransmitted with more frequently broken links which translate to higher delay difference between the varying and fixed link bandwidth cases.

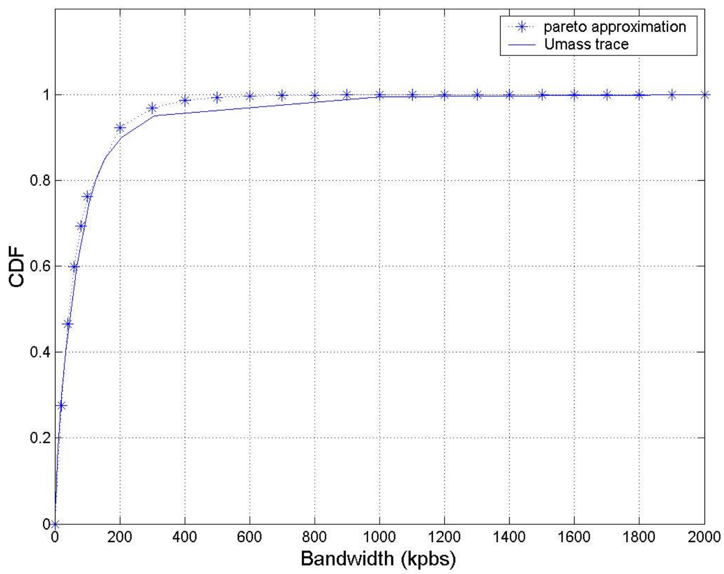


Figure 4: CDF of the link bandwidth from UMass Trace

	Total # of control messages	Total # of data messages	Transmitted bytes over generated bytes	Avg delay	Delivery Ratio	Avg Hop count
UMASS trace packet interval: 0.25pkt/s	118737	15580	10.8	286.9	99.1%	4.8
RWP Packet interval: 0.25pkt/s	113762	15098	10.3	259.4	98.6%	5.3
UMASS trace Packet interval: 0.5pkt/s	118495	24468	7.2	340.4	97.7%	4.3
RWP Packet interval: 0.5pkt/s	129156	36250	9.9	269.6	98.6%	5.1
UMASS trace Packet interval: 1pkt/s	149321	61352	7.6	497.6	98.7%	4.0
RWP Packet interval: 1pkt/s	172469	91232	11.3	428.3	99.2%	5.1

Table 5: Simulation Results using Fixed/Varying Link Bandwidth (max speed=5m/s, buffer size=1200 messages)

	Total # of control messages	Total # of data messages	Transmitted bytes over generated bytes	Avg delay	Delivery Ratio	Avg Hop count

UMASS trace Packet interval: 0.25pkt/s	58837	9369	6.1	496	99.2%	3.5
RWP Packet interval: 0.25pkt/s	56842	12585	7.4	351	99.6%	4.3
UMASS trace Packet interval: 0.5pkt/s	61380	17354	4.7	549	99.6%	2.6
RWP Packet interval: 0.5pkt/s	66181	24996	6.5	376	99.4%	4.1
UMASS trace Packet interval: 1pkt/s	79416	28451	3.2	794	98.9%	2.3
RWP Packet interval: 1pkt/s	83036	39256	4.2	383	99.5%	3.4

Table 6: Simulation Results using Fixed/Varying Link Bandwidth (max speed=20m/s, buffer size=1200 messages)

E. *Comparison between two hop and multihop approaches*

In this section, we present the simulation results we obtained by comparing the two hop approach with the multihop approach. For the two-hop approach [23], we assume that nodes exchange hello messages with one another periodically. This allows them to build a neighbor table. In addition, we assume that each encoded message is divided into eight blocks at the source node. Upon meeting a new 1-hop contact, the source node sends a data block to that new neighbor. Thus, all eight blocks will be disseminated (to eight contacts). The contacts carry the block until they meet the destination. If that happens, a contact will deliver the message block. As long as the destination receives four out of the eight blocks, that message is considered successfully delivered to the destination.

Table 7 shows the performance of the two-hop relay approach while Table 8 (Table 2 repeated here) shows the performance of the multihop approach with the random waypoint mobility model. The results indicate that when the mobility is low, the performance of two-hop relay approach is not good. The delivery ratio drops drastically as the network becomes sparser. Due to the low mobility, the nodes may not encounter one another throughout the duration of the simulation and hence the delivery ratio is low as the network grows sparser. With a sparser network, there are fewer contacts and hence the overhead also drops. However, the delivery ratio is maintained at more than 98.6% using multihop routing approach. In addition, the 95 percentile delay achieved by the multihop approach is significantly smaller than the 2-hop approach. This improvement in delivery ratio and packet delivery latency comes at the price of larger overhead when compared to the two-hop approach.

Node Density	Delivery Ratio	Average Delay	Overhead	Hop count	95% Dly
4.0×10^{-5}	95.3%	381	9.84	2	950
1.8×10^{-5}	78.4%	1724	7.73	2	2250
1.0×10^{-5}	41.9%	1222	6.23	2	3300

Table 7: Performance of 2-hop approach using random waypoint mobility model

Node Density	Delivery Ratio	Average Delay	Overhead	Hop count	95% Dly
$4.0x10^{-5}$	100%	1.59	10.49	3.9	2.4
$1.8x10^{-5}$	99.99%	43.4	13.16	5.7	2.7
$1.0x10^{-5}$	98.6%	259.4	10.39	5.25	1600

Table 8: Performance of multihop approach using random waypoint mobility model

Tables 9 & 10 summarize the simulation results obtained for two-hop and multihop approaches respectively when ZebraNet mobility model is used. The results show that the 2-hop approach achieves relatively good performance. It seems that this 2-hop approach has been specifically tuned for ZebraNet mobility model. The multihop approach still performs slightly better than the two-hop approach. It has slightly higher delivery ratio and significantly better 95% delay when compared to the two-hop approach. This again comes at the price of incurring larger overhead.

Node Density	Delivery Ratio	Average Delay	Overhead	Hop count	95% Dly
$4.0x10^{-5}$	96.8%	710	7.02	2	420
$1.8x10^{-5}$	96.5%	366	8.01	2	950
$1.0x10^{-5}$	98.99%	128	10.3	2	1500

Table 9: Performance of the two-hop approach using ZebraNet mobility model

Node Density	Delivery Ratio	Average Delay	Overhead	Hop count	95% Dly
$4.0x10^{-5}$	99.99%	0.71	9.32	2.1	3
$1.8x10^{-5}$	99.99%	29	14.45	4.1	130
$1.0x10^{-5}$	99.99%	203	14.77	3.5	700

Table 10: Performance of the multihop approach using ZebraNet mobility model

IV. INTERGROUP ROUTE DISCOVERY

In some network scenarios, one group of nodes (say Group 1) may not be able to hear another group of nodes (say Group 3) directly but they may hear members of a third group (say Group 2) that can communicate with Group 3 as shown in Figure 5. In such scenarios, different groups may use different algorithms to route packets within their own groups. To enable intergroup communications, we assume that different groups are willing to support a few common intergroup route messages to facilitate the ability for nodes from one group to route packets destined to another group. To minimize the need for all nodes to support inter-region routing, a gateway selection protocol [16] is used whereby only nodes which have been selected as gateways need to run an intergroup routing protocol.

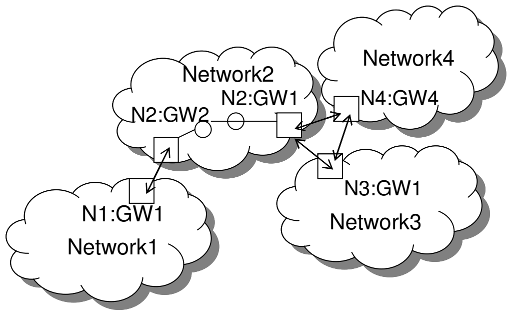


Figure 5. Intergroup Routing

Here, via an example with a message ferry, we describe how the nodes in a DTN environment can discover routes to other nodes. In Figure 6, we have forty nodes that are partitioned into four isolated groups. There is a base station node in each group. The base station node is assumed to have a second long range radio that provides wireless backhaul link with higher bandwidth. To minimize the risk of potential enemy detection or energy consumption, the wireless backhaul links are only turned on periodically for short durations of time. In the example shown in Figure 6, we assume that BS1 (BS2) can communicate only occasionally with BS2 (BS3). Similarly, BS3 can communicate only occasionally with BS4.

Because these groups are isolated far away from one another, the groups can only communicate with one another either via the wireless backhaul links that are not always available or via the message ferry. We assume that the message ferry broadcasts a service announcement message periodically as it moves along a fixed route. We also assume the service announcement message contains information on the groups that the message ferry can reach from previous trips. Other useful information like the estimated next visit time to those reachable groups may be included for more sophisticated forwarding decisions.

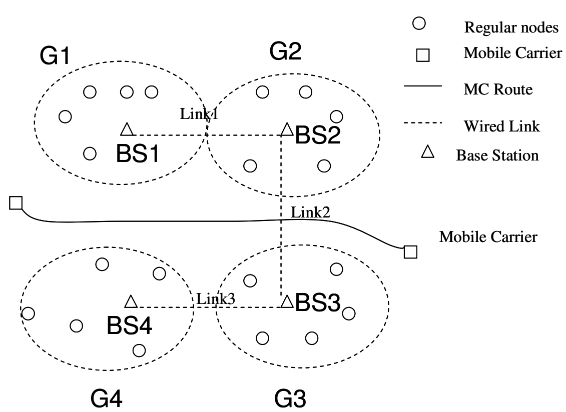


Figure 6. A 4-group DTN example

We assume that the intragroup routing protocol makes use of the information provided by the underlying ad hoc routing protocol which is again assumed to be DSR-like [7]. Whenever there is intergroup traffic, the nodes will evaluate to see if it consumes less cost (e.g., in terms of expected delivery delay) to send the traffic via the backhaul links or via the message ferry if both types of forwarding services are available. The base station will send announcements to inform the nodes whether or not it can provide intergroup forwarding services. For example, when Link 1 is not available, BS1 will inform all members in group 1 that intergroup service is not available. Similarly, when Link 2 is not available, BS2 will inform BS1 that it cannot communicate with Group 3. Then, BS1 will inform Group 1 members that intergroup service to Group 3 is not available. Note that BS2 can delay such notification until its buffers are full or can notify BS1 immediately when Link 2 disappears.

Assume that Group 1 needs to communicate with Group 3; then a source node (a node in Group 1) will send the traffic to BS1 and BS1 will forward it to BS2 when Link 1 is available. If Link 2 is not available, the messages will be stored at the buffers at BS2 until Link 2 is available. Drop-from-front scheme can be used to replace old messages with new messages when the buffer at a base station is full. However, one can also use tail-drop scheme where no new messages will be accepted when the buffer at the base station is full. In addition, when different classes of messages are available, smarter buffer management schemes will be needed to give different treatments to messages from different classes.

When the base station does not provide intergroup service or if the cost for sending such traffic using the backhaul route is higher than using a route via the message ferry, the regular nodes will use the service from the message ferry. Not all nodes can hear the message ferry. We assume that all nodes within a group that can hear the service announcement from a message ferry can provide forwarding services to/from the message ferry. Such nodes serve as gateway nodes. The gateway nodes can make periodic announcements to their group members that they can provide forwarding services. All regular nodes can cache the gateway information for future use. The above approach is more proactive since the nodes within a group can find out where the gateway nodes are before they need to use the forwarding services from such nodes. Alternatively, the sending nodes can send gateway discovery messages to discover the gateway nodes. Once a sending node can identify a gateway node, it can then send intergroup traffic to that gateway node. This approach is more reactive and message delivery time may increase due to the need to perform gateway discovery.

V. Performance Studies of Intergroup Communications using a Message Ferry

Using the network topology shown in Figure 6, we wish to investigate the performance that can be achieved for intergroup communications when wireless backhaul links and a message ferry are deployed. In this section, we report extensive simulation experiments to evaluate the impact of the custody transfer feature, and the use of a message ferry on the message delivery ratio when the availabilities of the wireless backhaul links are varied both in terms of the relative on-off patterns and the percentages of their availabilities. We also explore the impact of having limited buffers at the base stations and regular DTN nodes on the end-to-end message delivery ratio. We use ns-2 [8],[9] for our simulations. The common parameter values used in the simulation are tabulated in Table 11. Each group has ten nodes which are randomly distributed over an area of 1000m by 1000m. Thus, each group forms a sparse ad hoc network. All nodes support DTN functionalities. The regular nodes move according to the random waypoint mobility model with a maximum speed of 5 m/s. We assume that the regular DTN nodes communicate with one another via the 802.11 links with 2 Mbps link bandwidth, while the wireless backhaul link has a bandwidth of 5Mbps. The link availability patterns used for the backhaul links are shown in Figure 7. The on/off times follow an exponential distribution with a certain mean on/off times to mimic link patterns shown. In Case 1 and Case 2, each link is available for an average of 20 seconds and not available for an average of 80 seconds if the mean on/off time is 100 seconds for a link availability of 20%. The two on/off patterns only differ in the relative positions of the link availabilities. To achieve the on/off patterns shown as Case 1 in Figure 7, we generate a random on time for link 1 (say x1), then schedule for link 2 to be on only after link 1 turns off, and link 2 will be on for another random on time (say x2), etc. In Case 3, each link is available for an average of 30 sec and not available for an average of 120 sec. So, the link availability is also 20%.

We assume that only one type of message is used and that the message has a fixed size of 512 bytes. We further assume that the message ferry has a buffer size of 400 messages. For each experiment, we measure the delivery ratio for the messages delivered via the wireless backhaul links and the message ferry separately. We also measure the contact time a message ferry has with a particular group during its route to help us understand the delivery ratio in each experiment. In addition, we also record the end-to-end message delivery times.

There are 10 pairs of traffic sessions where 4 pairs are single hop pairs (meaning requiring a traversal of only one backhaul link for delivery), 4 pairs are 2-hop pairs (meaning requiring a traversal of two backhaul links for delivery), and 2 pairs that are 3-hop pairs (meaning it needs to traverse 3 backhaul links) when the message ferry service is not available.

A. *Impact of custody transfer on delivery ratio*

In our first set of experiments, we investigate how the custody transfer feature helps in the message delivery ratio. The backhaul link follows an on/off pattern shown in Figure 7 (Case 1) with a mean on/off cycle time of 100 seconds and a link availability of 20%. We set the base station and the message ferry buffer size to be 400 messages. The buffer size for regular DTN nodes is set to 100 or 200 messages. We simulated four scenarios, namely, a) backhaul delivery without custody transfer, (b) backhaul delivery with custody transfer, (c) ferry delivery without custody transfer, and (d) ferry delivery with custody transfer.

Parameter	**Value**
Simulation Areas	2000mx2000m
Group Size	10 nodes/group
Wireless Link	802.11(2M)
Wired Link	duplex link(5M)
Packet Size	512bytes/packet
Traffic Pattern	CBR (interval:4sec/packet)
Buffer Size of Regular Nodes	Depending on experiments
Buffer Replacement Policy	Drop-from-front
Max Speed of Regular Nodes	5 m/s
Buffer of the Mobile Carrier	400 messages
Speed of the Mobile Carrier	15m/s
Traffic Load	10 pairs
Simulation Time	5000 seconds

Table 11: Common Simulation Parameter Values

The message delivery ratios achieved in these four scenarios with link on/off periods of 100 seconds are tabulated in Table 12(a). Our results show that the custody transfer feature improves the message delivery ratio significantly to near 90-92% with only the backhaul delivery mechanism and 89.4% (with 200 message buffers) with only the ferry delivery mechanism. The lower message delivery ratio for the message ferry case is due to the highly disruptive intragroup routes to the gateway nodes since each group is a sparse ad hoc network. We also investigate how the on/off period affects the backhaul delivery ratio by repeating the experiment with an on/off period of 200 seconds. The results are tabulated in Table 12(b). The results show that the backhaul delivery ratio drops by about 20% without the custody transfer when the on/off period increases from 100 seconds to 200 seconds but with custody transfer, the drop is only about 3%.

Table 12(a): Message Delivery Ratio for Experiment 1 with on/off period of 100 sec

Buffer Size	100	200
Backhaul-delivery without custody-transfer	55.6%	58.4%
Backhaul-delivery with custody-transfer	90.9%	92.3%
Ferry-delivery without custody-transfer	10.3%	11.6%
Ferry-delivery with custody-transfer	78.6%	89.4%

Table 12(b): Message Delivery Ratio for Experiment 1 with on/off period of 200 sec

Buffer Size	100	200
Backhaul-delivery without custody-transfer	44.9%	45.9%
Backhaul-delivery with custody-transfer	87.5%	91.1%

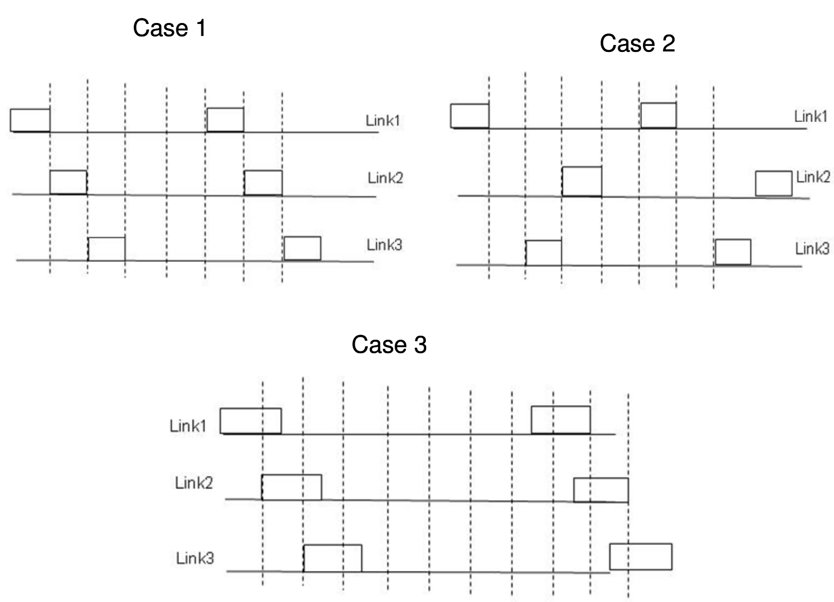


Figure 7. Various Link Availability Patterns

B. *Impact of Link Pattern on End-to-end Message Delivery*

In our second experiment, we set the mean on/off period to be 200 seconds. The custody transfer feature is turned on. The DTN nodes only use the backhaul links (no message ferry service is provided). The results are tabulated in Table 13. The number expressed in seconds is the mean end-to-end message delivery time.

Table 13: Message Delivery Ratio and Mean End-to-end Message Delivery Time for Experiment 2

	Link Pattern 1	Link Pattern 2	Link Pattern 3
1-3 pair	78.7% 277.2seconds	82.0% 410.8second	75.1% 385.9seconds
3-1 pair	86.7% 352.5seconds	84.7% 337.1seconds	82.1% 306.4seconds
2-4 pair	96.2% 131.4seconds	97.0% 278.3seconds	99.1% 144.5seconds
4-2 pair	96.0% 229.3seconds	97.0% 145.9seconds	96.9% 166.9seconds
1-4 pair	75.9% 188.1seconds	77.4% 432.0seconds	79.3% 239.3seconds
4-1 pair	85.0% 444.6seconds	96.8% 240.9seconds	72.2% 345.7seconds
1-hop pairs	88.7% 138.5seconds	89.4% 148.3seconds	87.9% 193.7seconds

There are a few interesting observations that we can make from these results. First, the delivery ratio for the traffic session between Group 1 and Group 3 (indicated by 1-3 pair) is lower than other pairs because the route between the source node and the base station breaks more frequently than other traffic pairs, e.g., Group 3 to Group 1. The mean end-to-end delivery time depends on various factors, e.g., the link availability pattern, the connectivity between the source node and the base station, etc. For example, even though session 1-3 and session 3-1 are both 2-hop pairs, the average end-to-end message delivery time for session 3-1 is higher than that achieved for session 1-3 using Case 1 link patterns because the traffic from Group 3 requires at least two on/off cycles to reach Group 1 but the traffic from Group 1 to Group 3 only needs one on/off cycle. In general, the mean end-to-end message delivery times are higher for traffic sessions that traverse more backhaul hops. However, there may be situations where this is not true. For example, the mean end-to-end delivery time for traffic session 1-4 is smaller than the mean end-to-end delivery time for traffic session 1-3. This is due to the fact that the source node for this 1-3 pair is sparsely connected to the base station in Group 1 while the source node for the 1-4 pair has a very reliable route to the base station in Group 1.

C. Buffer Size Study

In the third experiment, the nodes use: (a) only the backhaul links, (b) only the message ferry, or (c) both backhaul links and message ferry to deliver intergroup traffic. We set the message ferry and base station buffer size to be 400 messages each. We then vary the buffer size of the regular DTN nodes to see what its impact on the message delivery ratio and end-to-end message delivery times. The link on/off pattern for Case 1 with a mean on/off cycle of 200 seconds and link availability of 20% is used for this third experiment. The results for the message delivery ratio, the end-to-end message delivery time (denoted as delay in Figure 9) and the overhead of control messages sent are plotted in Figures 8, 9, and 10. The results indicate that a delivery ratio of 90% is achievable even with 20% link availability.

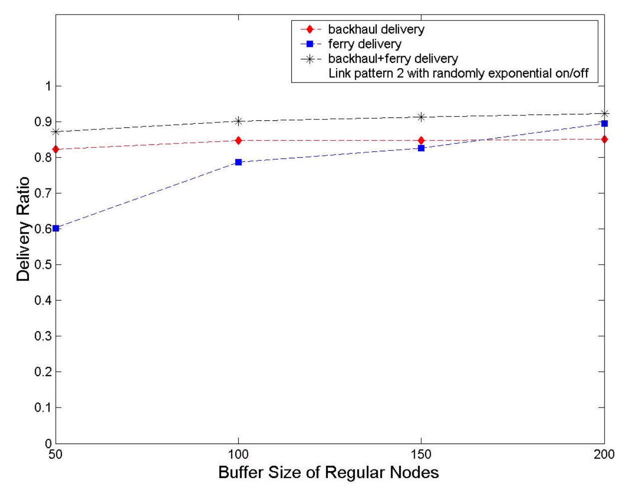


Figure 8: Message Delivery Ratio

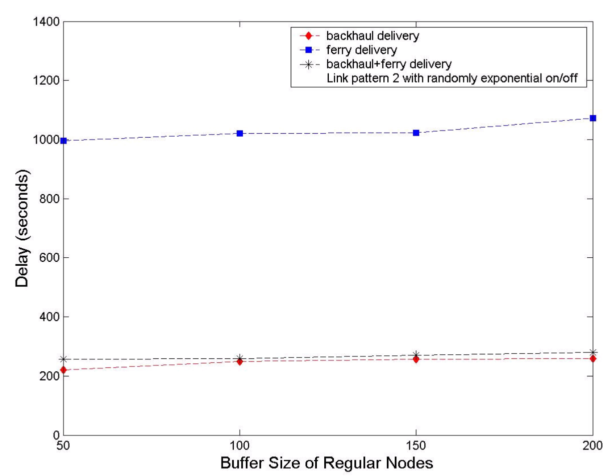


Figure 9: End-to-end Message Delivery Time

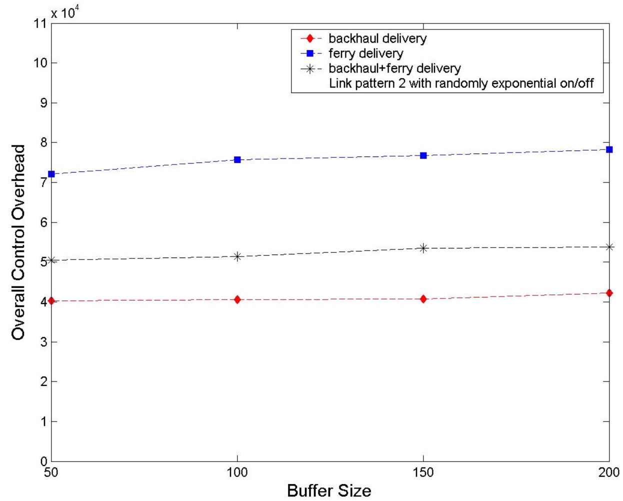


Figure 10: Overall Control Overhead

D. *Intergroup Scenario with Two Ferries*

In this section, we explore another intergroup communication scenario. In Figure 11, we have the same 4 groups of nodes as shown in Figure 6 except that there are no backhaul links. We consider two subcases, namely (a) with single ferry, and (b) with two ferries. Each ferry takes a fixed route that looks like a horizontal "8" shape as shown in Figure 11. When there are two ferries, they travel in opposite directions. F1 starts from location S_1 while F2 starts from location S_2. Each ferry moves at a speed of 15 m/s. In each ferry cycle, the two ferries can communicate with one another at two locations –at points marked as M_1 or M_2. There are 10 pairs of intergroup flows. In our first set of experiments, we fix the traffic load at 0.25 pkts/sec and vary the buffer size. We perform two sets of experiments to compare the performance using one or two ferries.

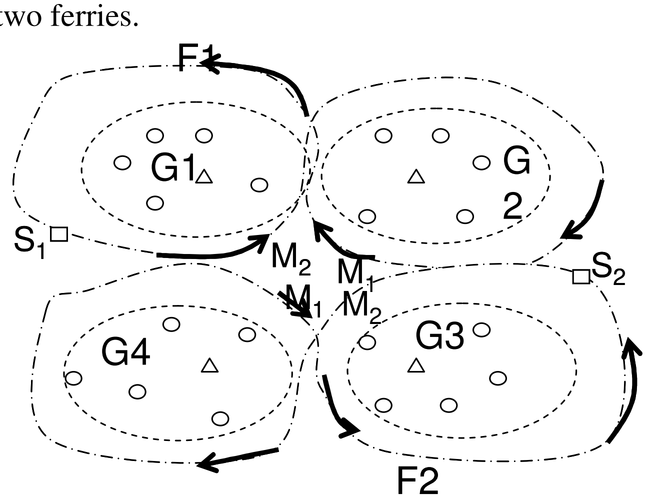


Figure 11: One/Two Ferry Scenario for intergroup communication

Figures 12-14 plot the results we obtained for delivery ratio, the average packet delay and the routing overhead respectively. The results indicate that the delivery ratio improved by 8% (with buffer size=200) with two ferries compared to the case with one ferry and the average packet delay was cut by nearly half with two ferries. As far as overall control overhead is concerned, the presence of an additional ferry decreases the overhead by 12%. This is because with more ferries, the routes are shorter (i.e., fewer hops) and hence more stable.

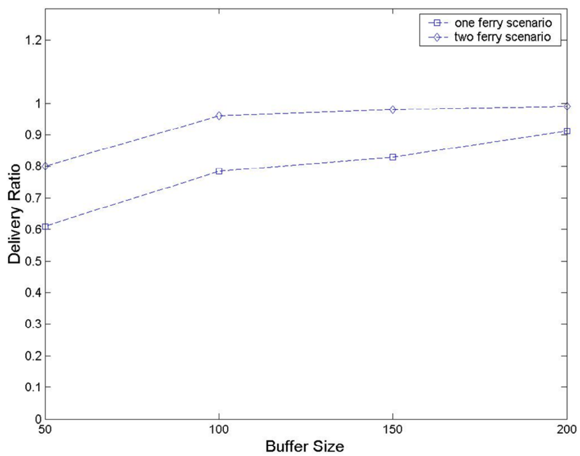


Figure 12: Delivery Ratio vs Buffer Size

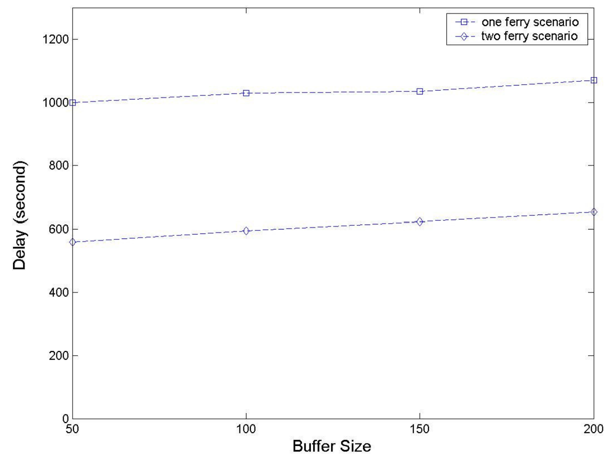


Figure 13: Avg Pkt Delay vs Buffer Size

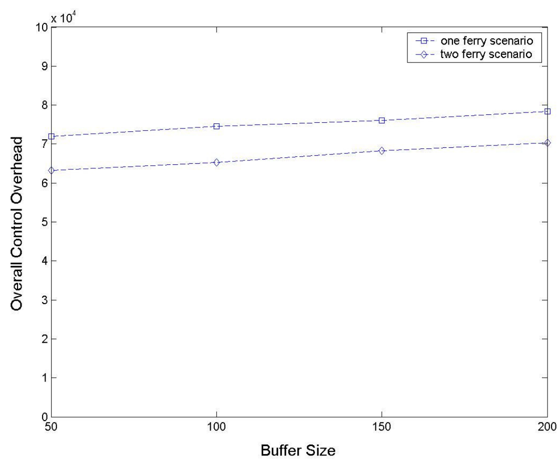


Figure 14: Overall Control Overhead vs Buffer Size

In our second set of experiments, we fix the buffer size at 200 messages and vary the traffic load from 0.25 pkt/sec to 2 pkt/sec and see what performance differences one or two ferries have. The results for the second set of experiments are plotted in Figures 15-17 below.

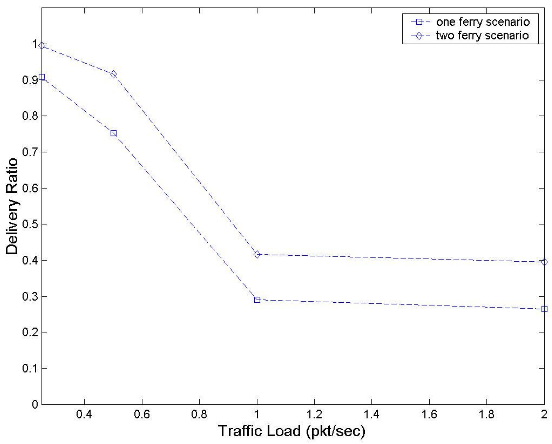


Figure 15: Delivery Ratio vs. Traffic Load

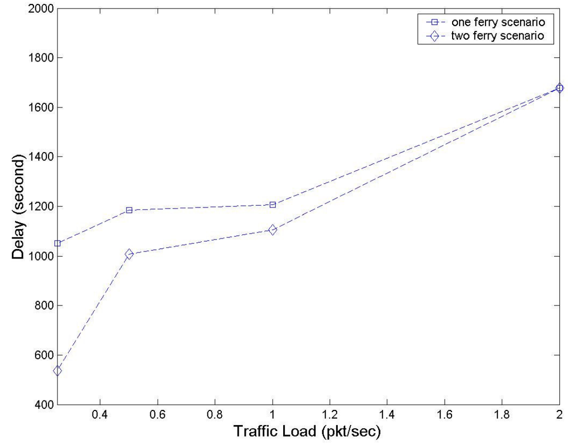


Figure 16: Avg Pkt Delay vs. Traffic Load

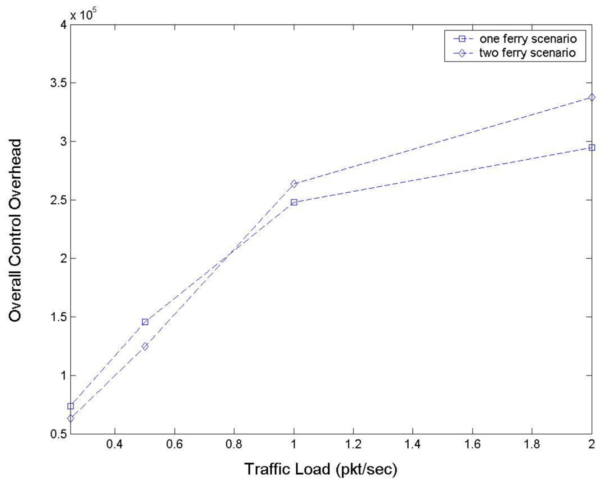


Figure 17: Overall Control Overhead vs. Traffic Load (Buffer=200 msgs)

Figure 15 shows that the delivery ratio drops significantly with increasing traffic load. The low delivery ratio is due to buffer overflows. Thus, we repeat the same experiments with a buffer size of 800 messages. The results are plotted in Figures 18 to 20. We see that compared to the delivery ratio achieved with a buffer size of 200 messages, the delivery ratio with a buffer size of 800 messages has significantly increased. With 2 msgs/sec, the delivery ratio in the 2 ferries scenario has increased from 40% (shown in Figure 15) to 83% (shown in Figure 18). The delivery ratio in the single ferry scenario also has increased from 28% to 51% as the buffer size increases from 200 to 800 messages. From Figure 19, we also observe that as the traffic load increases beyond 1 msg/sec, the average packet delay with single and two ferries becomes very similar. The average packet delay consists of three components, namely (a) the multihop delay in reaching a node that can communicate with a ferry, (b) the waiting time for a ferry to arrive, and, (c) the ferry transport time. At low traffic load, the average packet delay is dominated by the delay components (b) & (c) so having a second ferry helps in reducing the average packet delay. At high traffic load, the delay component in (c) dominates and hence there is not much difference between the average packet delay with single and double ferries.

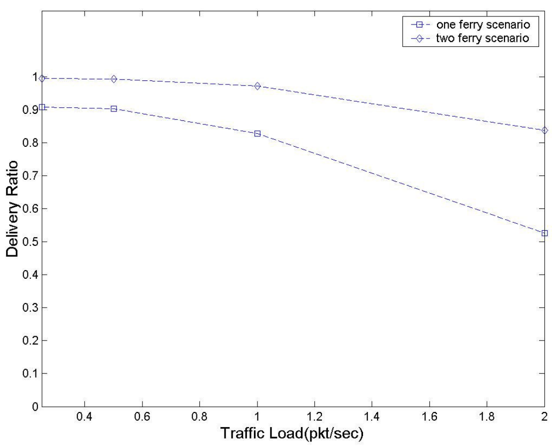


Figure 18: Delivery Ratio vs. Traffic Load (Buffer=800 msgs)

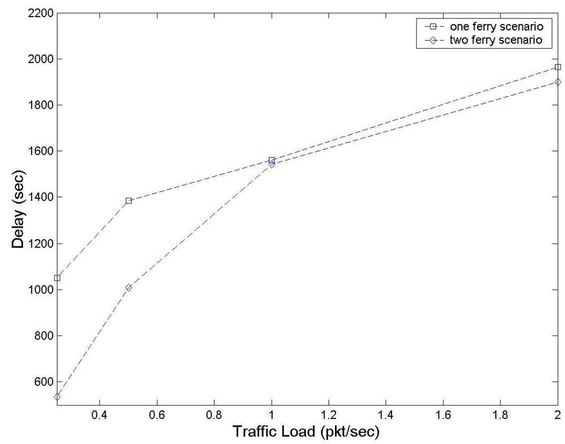


Figure 19: Avg Delay vs. Traffic Load (Buffer=800 msgs)

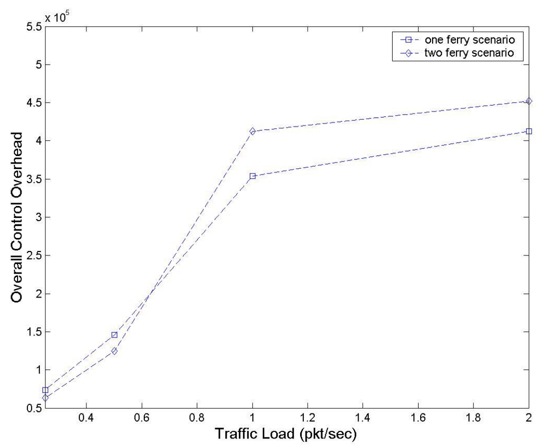


Figure 20: Overall Control Overhead vs. Traffic Load (Buffer=800 msgs)

The work in this section assumes that the message ferry route is fixed. More intelligent ferry route design schemes e.g. [15] can be designed to optimize the message delivery latencies.

VI. CONCLUDING REMARKS

In this paper, we have illustrated the usefulness of the custody transfer feature in an intragroup communication scenario and how the transmission overhead and achievable packet delivery latency vary in different mobility models. We also caution that the custody transfer feature alone does not guarantee communications in a very sparsely connected network. We propose to use message ferries for scenarios where the nodes are very widely distributed.

In addition, we investigated how the percentage of nodes supporting DTN functionality affects performance. Our results indicate that the delivery ratio achieved with only 50% nodes supporting DTN functionality can be as high as 96.5% (only 2.2% lower than that achieved with all nodes supporting DTN functionality) using the scenarios we have simulated. Our results also suggest that the two-way delay experienced in bidirectional flow is only about 10% more than the one-way delay with unidirectional flow. We also provide some results that compare the performance difference between two categories of routing protocols, namely the multihop approach and the two-hop approach. Our results indicate that the multihop approach still outperforms the two-hop approach. Using the traces provided by the UMass DieselNet group, we also investigate how the varying link bandwidth impacts the performance. Our simulation results indicate that the varying link bandwidth increases the average packet delay by about 24% compared to that experienced with fixed link bandwidth.

Via an example, we show that both the message ferry and the custody transfer feature can improve the end-to-end intergroup message delivery ratio in a scenario with multiple backhaul links where the link availability can be as low as 20%. In particular, our results indicate that one can achieve a delivery ratio as high as 90-99% with appropriate buffer allocations. The design factors that influence the end-to-end delivery ratio in scenarios where message ferries and backhaul links are used to connect partitioned groups of nodes include the backhaul link availability patterns, and buffer allocation strategies. Our results indicate that with appropriate buffer size, the intergroup message delivery ratio can be maintained at more than 80% with a single ferry and multiple backhaul links. We also simulate another scenario where there is no backhaul link but either one or two ferries are used for intergroup communications. With appropriate buffer allocation, we again show that high delivery ratio (as high as 83%) can still be achieved even without the presence of backhaul wireless links.

There are some topics that are worthwhile investigating further. In this paper, we assume that the traffic demands from one group to another do not vary with time and that the link availability follows exponential on/off distribution. In real world scenarios, the traffic demands and the link availabilities may be changing dynamically so one may not be able to predict the maximum required buffer size for the base station. So, some work needs to be done to estimate the maximum required buffer size given some rough estimates of the nodes' velocities, and mobility models in different environments. In this paper, we also simulated single and bidirectional flows. In the real world, there may be different traffic types [25],[26]. We intend to investigate the impacts of having different traffic types on the system performance especially when these different traffic types have different Quality of Service requirements (e.g., in terms of delivery latency). In addition, our results comparing different unicast routing schemes in DTN suggest that different schemes perform well in different scenarios and hence a hybrid scheme that combines the benefits of different schemes should be used to give the most flexibility.

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