Efficient Interdomain Multicast Delivery in Disruption Tolerant Networks

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Abstract

Mobile nodes in some challenging network scenarios suffer from intermittent connectivity and frequent partitions e.g. battlefield and disaster recovery scenarios. Disruption Tolerant Network (DTN) technologies are designed to enable nodes in such environments to communicate with one another. In the past, we have proposed two intradomain multicast routing schemes, namely the context-aware multicast routing (CAMR) and Encounter-based Multicast Routing (EBMR) schemes. In this paper, we consider the problem of routing multicast messages across different domains. We present a ferry based interdomain multicast delivery scheme where a ferry is used to deliver multicast messages across groups that are partitioned and a variant of the encounter-based multicast routing scheme is used as the intradomain routing scheme for intradomain delivery. We then present simulation results using different group mobility models to illustrate the usefulness of the scheme we design. Our results indicate that the scheme we design can achieve high delivery ratio with reasonable data efficiency. Our results also indicate that the delivery ratio seen using a more realistic VANET model is slightly worse than that seen using the RPGM model.

I. INTRODUCTION

With the advancement in technology, many users carry small computing devices e.g. PDAs, cell-phones etc with wireless interfaces. These devices can form mobile ad hoc networks and communicate with one another via the help of intermediate nodes. Such ad hoc networks are very useful in several scenarios e.g. battlefield operations, vehicular ad hoc networks and disaster response scenarios. Many ad hoc routing schemes have been designed for ad hoc networks but such routing schemes are not useful in some challenging network scenarios where the nodes have intermittent connectivity and suffer frequent partitioning. Recently, disruption tolerant network technologies [1],[2] have been proposed to allow nodes in such extreme networking environment to communicate with one another. Several DTN unicast routing schemes [3],[4] have been proposed. However, having an efficient delivery service for multicast traffic is equally important e.g. geographical map marked with potential locations of enemies need to be disseminated to soldiers from different platoons. One cannot directly apply the multicast approaches proposed for the Internet or well-connected mobile ad hoc networks to DTN environments because of the sparse connectivity among nodes in DTNs. Some DTN multicast routing schemes have been proposed, namely (a) Dynamic Tree Based Routing (DTBR) [9], (b) OS-Multicast [10], and (c) Context-Aware Multicast Routing (CAMR) [11]. However, these schemes are designed for networks where the nodes belong to the same administrative domain, and hence may not be scalable or efficient when being applied to a scenario with multiple domains.

In this paper, we consider a network scenario with multiple administrative domains. DTN multicast operations among nodes that belong to the same administrative domain are called intradomain multicast while the effort of delivering multicast traffic among different domains will be referred to as the interdomain multicast. We introduce an efficient interdomain multicast delivery scheme called the ferry-based interdomain multicast routing (FBIMR) scheme. Compared to the existing DTN multicast routing schemes which are designed for a flat structure e.g. the DTBR, OS-Multicast and CAMR schemes, the FBIMR scheme organizes the multicast structure hierarchically and hence minimizes the management states. Via simulations, we demonstrate that the FBMIR scheme coupled with an efficient intradomain scheme called the encounter-based multicast routing with redundancy (EBMR2) scheme achieves high delivery ratio, low message delivery latency, and reasonable transmission efficiency.

The rest of the paper is organized as follows: In Section II, we discuss related work. In Section III, we present the details of the FBIMR and the EBMR2 schemes. In Section IV, we present our simulation results. We conclude in Section V.

II. RELATED WORK

A. *Multicast Routing Scheme for MANETs*

Many multicast protocols have been proposed to address the challenge of the frequent topology changes in mobile ad hoc networks. In ODMRP [13], a multicast mesh rather than a tree is created from the source to reach the receivers that are moving in the networks. Simulation results have indicated that ODMRP can achieve reasonably good message delivery ratio because with a multicast mesh, multiple paths can be explored to reach different receivers. However, ODMRP does not work well in sparsely connected mobile ad hoc networks.

B. DTN Routing Schemes

Various DTN unicast routing schemes have been designed. These different schemes can be grouped into three categories. The first category [5] uses special nodes called ferries to deliver messages between partitioned networks. Ferry routes have significant effects on the data delivery performance, hence they need to be designed efficiently. The second category [3],[4] uses multihop routing approach where contact history information is used to determine the next hop node to pass a message. The third category [7],[8] uses a two-hop routing approach where the intermediate nodes that receive messages from any source have to store the messages until they can deliver the messages when they come into contact with the destinations of the messages. Sometimes, erasure-coding is used to increase the chances of a receiver getting a particular message. In an erasure-coding based scheme, a message is first encoded, and then divided into multiple blocks. These blocks are sent to different relays. The destination only needs to receive a certain fraction of the encoded blocks to reconstruct the original message.

Several multicast routing schemes have also been designed for DTNs, namely (a) DTBR [9], (b) OS-Multicast [10], and (c) CAMR [11]. DTBR is a tree-based multicasting algorithm. DTBR assumes that each source node of the multicast group has complete knowledge or a summary of the link states in the network. During the lifetime of a multicast session, DTBR requires an upstream node to assign the receiver list for its downstream nodes based on its knowledge of the current network topology. The downstream nodes are allowed to forward bundles only to the receivers in the list. However, since the network topology changes frequently, it is not easy to maintain the multicast delivery tree. In addition, the receiver list cannot be adjusted by intermediate nodes once it is decided by upstream nodes, which means newly discovered delivery opportunities cannot be used by intermediate nodes.

OS-multicast [10] was proposed to overcome a limitation of DTBR. Unlike DTBR, OS-multicast let each intermediate node maintain a tree rooted at itself to all the receivers and adjust the receiver list according to local knowledge of the network topology. Via simulations, the authors [10] show that OS-multicast achieves good performance when the probability of the link unavailability is high. However, all simulations are based on a network of 25 nodes deployed in a 1000×1000 m^2 area, which is still quite well-connected. The authors in [11] show that the performance of OS-multicast degrades when the network becomes sparser. Moreover, OS-multicast still relies on a DSR-like route discovery process to build a knowledge base of the current network topology. Such a process will not work in a very sparse network environment.

In [11], the authors propose the CAMR scheme where nodes are allowed to use high power transmissions when the locally observed node density drops below a certain threshold. Each node maintains 2-hop neighborhood information, and hence can deliver traffic without invoking a route discovery process if all receivers are within its two-hop neighborhood. In addition, the nodes are allowed to act as message ferries when they discover they are in a very sparse neighborhood. The combined high-power route discovery process and message ferrying features allow CAMR to achieve much higher multicast delivery ratio than DTBR and OS-multicast schemes. However, CAMR still relies on a route discovery process that is similar to the traditional ad hoc routing approach, and also relies on the ability to control node movement. Such reliance means CAMR may not be feasible in some scenarios e.g. battlefield operations. The EBMR2 scheme we design in this work does not have such limitations.

In [12], the authors propose SHIM, a scalable hierarchical interdomain multicast routing scheme. In SHIM, the group leaders form the upper layer while the rest of the nodes from different groups form the lower layer. A multicast source sends its traffic to its group leader and the group leader will distribute the packets to all group leaders which have interested receivers. The main drawback of this scheme is that it uses either DTBR or OS-Multicast as the intradomain multicast routing scheme. Neither of these two schemes performs well in very sparse scenarios because they rely on a DSR-like approach to find a route between two group leaders.

III. SYSTEM MODEL

In this work, we assume a network with M domains (or groups) of mobile nodes. Subsequently, we will use the word "group" to represent nodes from a particular domain. There is a group leader, and one or more message ferry(ferries) within each domain. Every node within a domain knows the group leader's and the ferry's (or ferries') identifier(s). Each group leader or ferry is equipped with GPS and a long range radio. Thus, the group leaders and the ferries form an upper layer network while the rest of the nodes form the lower layer network.

IV. AN INTEGRATED MULTICAST DELIVERY APPROACH

In our network, each node periodically broadcasts a beacon. The beacon message includes its delivery predictabilities to other nodes in the network. As in the Prophet [3] scheme, each node updates its own delivery predictabilities to nodes within its own group according to the following three equations:

$$P(a,b) = P(a,b)_{old} + (1 - P(a,b)_{old}) * \alpha \qquad \text{----- Eq(1a)}$$

$$P(a,b) = P(a,b)_{old} * \gamma^k \qquad \text{----- Eq(1b)}$$

$$P(a,c) = P(a,c)_{old} + (1 - P(a,c)_{old}) * P(a,b) * P(b,c) * \beta \qquad \text{--Eq(1c)}$$

Eqn 1(a) allows a node to update the metric whenever a node is encountered so that nodes that are often encountered have high delivery predictability, and α is an initialization constant chosen from the range [0,1]. Eqn 1(b) is used to reduce the delivery predictability if two nodes do not encounter each other for a while. In Eqn 1(b), γ is the aging constant and k is the number of time units that have elapsed since the last time the metric was aged. Eqn 1(c) is the equation used for the transitivity property. It shows how this transitivity affects the delivery predictability where β is a scaling constant that decides how large impact the transitivity should have on the delivery predictability. In [3], α is set to 0.75, β is set to 0.25 and γ is set to 0.98.

To support the delivery of multicast traffic across different groups, three main components need to be designed. These three main components are (a) group membership subscription and maintenance which deals with how a node from a different group can subscribe to a multicast group initiated by another group, and how group membership can be maintained without keeping many states, (b) the interdomain multicast delivery which deals with transporting the multicast traffic from one group to another, and (c) the intradomain multicast delivery which discusses how the interdomain multicast traffic will be delivered to nodes within a group once it is received from an outside group. Each of these topics will be discussed in details in the subsequent sub-sections. Besides these three components, security design also needs to be explored but this topic is considered out of scope for this paper.

A. *Group Subscription and Membership Maintenance*

The domain (or group) where a multicast source originates is called the source domain (group). A multicast source will send its group advertisement to its own group leader. In addition, any node that wants to join (or leave) a multicast group sends a join (or leave) message to its own group leader. The group leader periodically broadcasts an aggregated message containing all group advertisements to its local nodes. The group leader also sends an aggregated message containing (a) all group advertisements from its local group, (b) join/leave messages for outside multicast groups to its group's message ferry. When the condition (to be described in the subsection B) for the ferry to move is satisfied, then the ferry will visit other domains and pass the appropriate multicast traffic and control messages to the group leaders of outside domains. When the ferry visits other groups, it collects the subscription information for all multicast groups initiated by its local group members from their group leaders

A group leader only needs to keep information regarding (a) which outside group subscribes to any multicast group hosted by its own group, and (b) nodes from its own group that join multicast groups. Such a hierarchical approach reduces the amount of membership states each group leader needs to maintain. Fig 1 gives an illustrative example how this process works. In this example, there are currently two multicast groups: MG_1 which is hosted by group 1, and MG_2 which is hosted by group 2 (with the symbol O that indicates outside). Two nodes labeled as $R_{11}(1)$ and $R_{12}(1)$ from Group 1 join MG_1, and two other nodes labeled as $R_{11}(2)$ and R_{12} (2) from Group 1 join MG_2. There are some nodes from two outside groups, namely Group 2, and Group 3 which also join MG_1. The table in Fig 1 shows the membership information maintained by the group leader of Group 1, GL_1. It shows that only the identifiers of the outside group leaders that subscribe to any multicast group hosted by a group need to be maintained by its group leader. It also shows that the identifiers of its local members for any outside group (e.g. MG_2 has a label "O" to denote this is hosted by an outside group) are maintained. If many of its group members subscribe to an outside group, a group leader may decide to just flood the multicast traffic from this outside group to its local group and not maintained information about individual subscribers.

Membership Table maintained by GL_1

MG	Outside Groups	Local Members
MG_1 (L)	GL_2, GL_3	$R_{11}(1)$, $R_{12}(1)$
MG_2 (O)		$R_{11(2)}$, $R_{12}(2)$

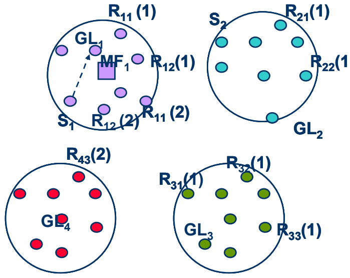
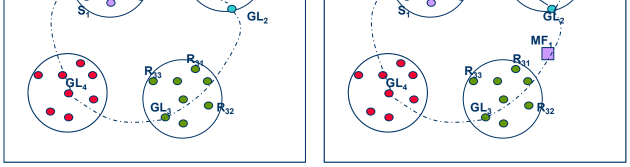


Figure 1: Maintenance of Group Membership by the Group Leader

B. *Interdomain Multicast Delivery*

Any multicast source will forward its traffic via an intradomain DTN unicast routing scheme to its group leader. The group leader will forward the multicast traffic generated by local groups to its local group members. In addition, the group leader also periodically floods group advertisements to its local group members. When a message ferry returns to its group leader, the group leader will check to see if it has collected enough messages e.g. multicast traffic, control messages like group advertisements and join/leave messages, destined for external groups to fill a ferry's buffer. If it does, it immediately sends all these messages to the message ferry, and the message ferry will leave immediately to visit other groups. If there are not enough messages, then the group leader initiates a 100-second timer. Before this timer expires, the group leader will periodically check its buffers to see if it has collected enough messages to fill a ferry's buffer. If so, it will stop the timer, send the messages to the ferry, and ask the ferry to leave. When the timer expires, the group leader will transfer all messages it has collected to the message ferry, and the message ferry will leave to visit other groups.



(a) the route taken by MF_1 (b) GL_2 delivers packets to receivers within Group 2

Figure 2: Ferry-Based Interdomain Multicast Routing Scheme (FBIMR)

Figure 2 illustrates the interdomain multicast delivery process. It shows a source S_1 sending its multicast traffic to its group leader, GL_1 . When one of the conditions for the message ferry to move is met, the ferry MF_1 moves from Group 1 to visit other groups, G_2, G_3, and G_4. The ferry will travel to a location where it can use its regular radio to reach the group leader of a visiting group, and then exchange packets with that group leader. The messages to be delivered to that visiting group are transferred first before the ferry picks up messages from the group leader of that visiting group. After getting the multicast messages from the visiting ferry, a group leader will use the intradomain multicast delivery scheme described in the next section to deliver the messages to all receivers of the multicast messages within its own domain. In Figure 2(b), we illustrate that GL_2 will distribute the multicast packets to R_{21}, R_{22} , and R_{23} after getting them from MF_1. We also show that the message ferry MF_1 will continue to visit Groups 3 and 4 after visiting Group 2.

C. Intradomain Multicast Delivery

For intradomain multicast traffic delivery, we use a scheme that is motivated by the multicopy unicast routing scheme reported in [14]. Our scheme is referred to as the encounter-based multicast routing with replication (EBMR2) scheme because each multicast packet can be replicated w times (referred to as w tokens) for each receiver to increase its chances of reaching all receivers. To accomplish this, each multicast packet has a header that includes the following information: (a) a receiver list, (b) the number of available replication tokens for each receiver. Each intermediate node that has a multicast message with a token value greater than one uses the binary spraying mechanism to spread its tokens to any node it encounters that does not have this message yet. When the token value becomes one, the intermediate node will then use the forwarding feature (which utilizes the delivery predictability values it maintains) to forward that multicast packet to any receiver.

Figure 3 illustrates how the EBMR2 scheme works. Let us assume that GL_2 needs to deliver a multicast packet to R_{21} , R_{22}, and R_{23}, and that the replication token value is set to 4.

The group leader GL_2 first encounters the node R_{23} at time t_0, and then the node n_{21} at time t_1. Besides delivering the multicast message to R_{23}, GL_2 also shares half of the tokens (i.e. 2 tokens) for that message with R_{23} so that R_{23} can use such tokens to deliver the message to other receivers. Then, GL_2 passes one token to node n_{21} at time t_1. After that, GL_2 only has one token left and hence can only use the forwarding feature which uses the delivery predictability values for decision making.

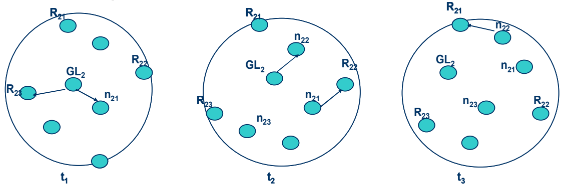


Figure 3: How EBMR2 scheme works

At time t_2, GL_2 meets n_{22} which has a higher delivery predictability to R_{21}. Thus, GL forwards its message to n_{22}. At the same time (t_2) , node n_{21} meets node R_{22}, and delivers the messages to that receiver. If node R_{23} can communicate with node n_{23} at time t_2, then R_{23} will also replicate its messages to node n_{23} . Such messages are redundant and will be removed if nodes n_{23} or R_{23} run out of buffer space or when the message expires. The buffer management policy used is the first in first out scheme. At time t_3, n_{22} forwards the message to R_{21}. The pseudo code for the EBMR2 scheme is shown in Figure 4.

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Intradomain Multicast Delivery
Each packet has a receiver list in the form {$r_1$, $r_2$, …, $r_{NR}$} where NR is the number of receivers for that multicast message. When a node n encounters node m, after updating its delivery predictability estimates, node n executes the following procedure:
 For every queued message j,
     pkt_exchange=0
  if (m is a receiver)
       pkt_change=2
  else {
   For every receiver d in the receiver list of the packets(j)
   if ($p_n$(d) <= $p_m$(d)) && ($p_m$ (d) > Th) && (token(d) >1))
                    pkt_exchange=1
                    include d in the new receiver list for packets(j)
    else if ((token(d)==1) && ($p_n$ (d) <=$p_m$ (d) && ($p_m$ (d) > Th))
                  pkt_exchange=2
   end if
   end receiver for loop
}
   if (pkt_change= =1)
       binary spread the message with appropriate receiver list
    to node m
   else if (pkt_change==2)
   forward the message to node m
   end if
end for message loop
```

Figure 4: Pseudo Code for the EBMR2 scheme.

We also consider another variant of the EBMR2 scheme which does no forwarding (referred to as the EBMR2-NF scheme). Each intermediate node can only spray the tokens if the number of tokens exceeds 1. Otherwise, they hold on to the message until they meet one of the receivers. The EBMR2-NF scheme performs binary spray when the token value of a message exceeds one and then performs 2-hop routing. Thus, the EBMR2-NF scheme is expected to give poorer delivery ratio but higher transmission efficiency than the EBMR2 scheme.

V. PERFORMANCE EVALUATION

A. Simulation Setup

To investigate the delivery performance of the integrated multicast approach that we have described in Section IV, we implement both the Ferry-Based Interdomain Multicast Routing Scheme and the EBMR2 scheme in NS-2 version 2.30 [12]. We set the threshold, *Th*, for the EBMR2 scheme to 0.5.

We assume each node has an 802.11-based radio which has a transmission range of 250m. We also assume that each node (including the ferry) has a buffer size of 1000 packets for traffic generated from the local group and 1000 packets for traffic generated from external groups.

Node Movement Model: In our default network scenario, we assume that there are four groups of nodes in a network with a size of 3000x3000m^2. There are 20 nodes within each group. Each group moves according to the Random Group Mobility Model [17] model where the movements of the group members are restricted around its group leader in a circular area with a radius of 500m. We also consider a larger network with 10 groups over an area of 6300x6300m^2. Each group has 10 nodes and they move according to the RPGM model within a circular area with radius 500m. The default average group speed is 3.0 m/s with a minimum speed of 1m/s and a maximum speed of 5m/s. There is one or more ferry(ferries) within each group that can visit the other cities. The default ferry speed is 15 m/s.

To ensure that our delivery scheme performs well in more realistic settings, we consider a vehicular ad hoc network with 4 subnetworks of vehicles, each subnetwork consists of 40 vehicles distributed over an area of 4Kmx4Km. We use the tool in [18] to generate the mobility traces for our NS-2 experiments. We extract four street maps (representing four cities) of size 4kmx4km from the US Census Bureau's TIGER database [19] into our simulation environment. The total area that encompasses these 4 cities is of size 12Kmx12Km. The transmission range we use is 250m so each subnetwork is a sparse network.

Data Item Generation Model: In our default traffic scenario, we assume that there are 4 multicast sessions with one multicast source in each session. The subscribers to each multicast session are nodes only from outside groups. The number of subscribers per session, and the multicast message rate are varied to study their impacts on the delivery performance.

The performance metrics that we use to compare different combinations of schemes are

- Delivery Ratio–This is defined as the number of messages successfully received by any receiver. $P_{succ} = \frac{\sum_{i=1}^{NR} msg\_recv(i)}{msg\_sent * NR}$ (where NR is the number of receivers).
- Average delivery latency – this is the average time it takes for the destination (or a receiver) to receive a message successfully.
- Data efficiency – this is measured as the number of useful data bytes over the number of total transmitted data bytes.

Each data point reported in the simulation results section is the average of 10 runs. The replication factor,w, is set to 4.

B. Simulation Results

1) Impact of Message Generation Rate

In our first experiment, we study the performance using the default network scenario with 4 groups of nodes moving according to the RPGM model within an area of size 3000x3000m^2. There are 4 multicast sessions. Each session has one source which generates packets at a rate of 1 pkt/s. There are 3 receivers from each outside group for each multicast session (a total of 9 receivers per session). The simulation results for both the EMBR2 and EBMR2-NF schemes are tabulated in Table 1.

The results indicate that the EBMR2 scheme achieves slightly higher delivery ratio, lower delivery latency but lower data efficiency than the EBMR2-NF scheme since the EBMR2 scheme explores more opportunities to deliver messages. The forwarding feature in the EBMR scheme allows the messages to be delivered faster than the EBMR-NF scheme.

Pkt/sec	0.25	0.5	1	2
Delivery ratio	0.96	0.95	0.92	0.75
Delay	123	127	141	152
Data Efficiency	0.20	0.19	0.18	0.18

Table 1(a): Delivery Performance vs Packet Rate (EBMR2)

Pkt/sec	0.25	0.5	1	2
Delivery ratio	0.95	0.93	0.90	0.74
Delay	131	138	152	159
Data Efficiency	0.23	0.23	0.23	0.22

Table 1(b): Delivery Performance s Pkt Rate (EBMR2-NF)

2) Impact of different numbers of receivers

Next, we study the impact of having different numbers of receivers. We use the same scenario where there are four groups of nodes with four multicast sessions as described in the previous section. Each multicast source generates packets at a rate of 1 pkt/s. We vary the number of receivers per outside group from 3 to 9. The results we obtained when either the EBMR2 or the EBMR2-NF scheme is used as the intradomain multicast routing scheme are tabulated in Table 2. Again, we see that the EBMR2 scheme achieves higher delivery ratio and lower delay than the EMBR2-NF scheme. The price to pay is smaller data efficiency.

The case where we have 6 subscribers per outside group is equivalent to having a total of 18 subscribers. The delivery ratio reported in [12] for a network with 40 nodes over 2500x2500m^2 (which is denser than the 40 nodes over 3000x3000m^2 scenario we study here) is only 0.25. Using the combined FBIM and EBMR2 scheme, we can deliver 380% more messages (our delivery ratio is 0.92). Even with the EBMR2-NF scheme, we get a delivery ratio of 0.90. Thus, it demonstrates that either the EBMR2 or the EBMR2-NF scheme works better than either the DTBR or the OS-Multicast scheme used in [12].

# of subscribers	3	6	9	12
Delivery ratio	0.92	0.92	0.91	0.90
Delay	141	146	153	157
Data Efficiency	0.18	0.29	0.31	0.614

Table 2(a): Delivery Performance vs # of Receivers/group (EBMR2)

# of subscribers	3	6	9	12
Delivery ratio	0.93	0.90	0.89	0.88
Delay	152	158	162	163
Data Efficiency	0.23	0.33	0.41	0.72

Table 2(b): Delivery Performance vs # of Receivers/group (EBMR2-NF)

3) *Impact of different numbers of sessions*

Next, we conduct an experiment using a larger network with 10 groups of nodes distributed over 6300x6300m^2. Each group has 10 nodes, and moves according to the RPGM model. The number of outside groups that join a multicast session is set to 6, and there are 3 receivers per outside group for each multicast session. The number of multicast sessions is varied from 4 to 8. Each multicast session has a source which generates multicast packets at a rate of 1 pkt/s. Four source groups are selected. Each source group has one or two multicast sessions.

Table 3 tabulates the results we obtained for the cases where either the EBMR2 or the EBMR2-NF scheme is used as the intradomain multicast routing scheme. We can see that as the number of multicast sessions increases, the delivery ratio drops because more packets are generated and need to be stored. The average round trip time for a ferry (having to visit 6 outside groups before returning) is 560s.

When there are 4 multicast sessions, each group leader at most receives local traffic from one multicast session. The intradomain delivery ratio is 0.93 with the EBMR2 scheme. Thus, each ferry will carry only FerryRTT*0.93 packets. If two ferries visit a group leader almost simultaneously, the group leader will see at most 2*FerryRTT*0.93 packets. From the simulation traces, such an event only happens 60% of the time. Thus, with a buffer size of 1000 packets, and FerryRTT=560s, the loss rate is at most 2.4% (1000/1040*0.6) for the transfers between the ferries to a visiting group leader. Thus, the effective end-to-end delivery ratio value is 0.93*0.93*0.976=0.844. The observed value from the simulations is 85% (EBMR2). Similar reasoning yields an estimated E2E delivery ratio of 0.74 for the EBMR2-NF scheme since its intradomain delivery ratio is 0.86. In addition, the average e2e delay is about 374s (280+47*2) (EBMR2) or 384s (EBMR2-NF) since a packet, on the average, needs to wait for 0.5*FerryRTT=280s, and the average intradomain delay with 4 sessions is 47s (EBMR2) or 52s (EBMR2-NF).

When the number of sessions increases to 8, each group leader receives a total of 2 pkt/s from its local multicast groups. With a buffer size of 1000 packets, the delivery ratio seen will be 1000/(560*2)=0.89. When its message ferry visits another group, its visit time may coincide with another ferry. When that happens, that visiting group leader sees 2000 packets (from two ferries) but only has a buffer size of 1000 packets, so a loss rate of 50% is incurred. Since this happens only 60% of the time, the effective delivery ratio from the ferry to a visiting group leader is 0.7(=1-0.6*0.5).The delivery ratio from this group leader to its own group members is 0.93. So, the effective end-to-end delivery ratio will be 0.89*0.7*0.92=0.57. The observed value from the simulation study is 53%. The data efficiency number is a bit misleading since it only considers successfully delivered messages. As the number of sessions increases, only messages that take fewer hops can be successfully delivered and hence the data efficiency value increases.

# of sessions	4	6	8
Delivery ratio	0.85	0.74	0.53
Delay	375	381	392
Data Efficiency	0.19	0.27	0.46

Table 3(a): Delivery Performance vs # of sessions (EBMR2)

# of sessions	4	6	8
Delivery ratio	0.72	0.62	0.39
Delay	383	389	397
Data Efficiency	0.22	0.32	0.52

Table 3(b): Delivery Performance vs # of sessions (EBMR2-NF)

4) *Impact of Mobility Model*

To understand if our scheme can work efficiently with different mobility models, we repeat our experiment using the VANET model described in Section V.A. We use the EBMR2 scheme as the intradomain multicast routing scheme.

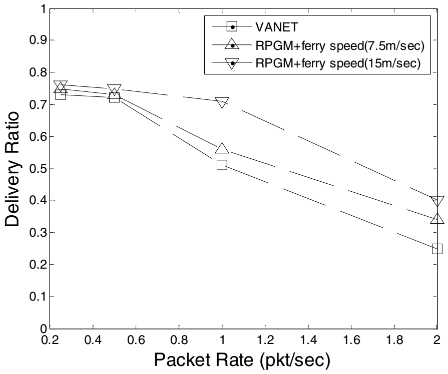
We simulate two scenarios. In the first scenario, there is a single ferry per sub-network. The ferry will transport the interdomain traffic from its local group to all other outside groups. In the second scenario, there are three ferries per sub-network. Each ferry is responsible for delivering the interdomain traffic from its local group to only one outside group. The ferry speed for the VANET model is fixed at 15m/s. The average intergroup ferry visit time for the VANET model is found to be about 400s.

We compare the results we obtain for the first scenario with the results we get for the scenario where there are 4 groups of nodes moving according to the RPGM model. For the RPGM model, the nodes within each group move within a circular area with a radius of 1400m while the group centers of these four groups move within an area of 12Kmx12Km. We tried two ferry speeds for the scenario with the RPGM model, namely 7.5m/s and 15m/s. The average intergroup ferry visiting times with a ferry speed of 7.5m/s and 15m/s for the RPGM model are 400s and 220s respectively. The ferry speed of 7.5m/s is chosen such that the average intergroup ferry visit time for the RPGM model is similar to that obtained for the VANET model.

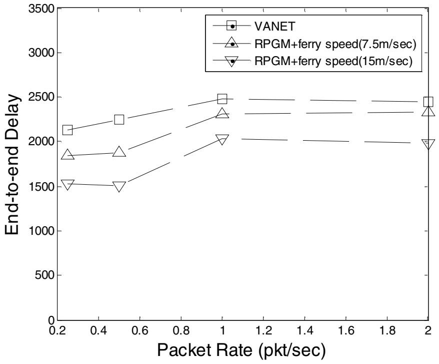
The plots in Figures 5(a), 5(b) and 5(c) plot the delivery ratio, the average message delivery latencies, and the data efficiency with the VANET and RPGM models. From the plots, we see that the delivery ratio with the RPGM model is much higher than that with the VANET model. For the VANET model, it takes 400s for each ferry to go from one group to another. Thus, the round trip ferry time is about 1600s. When the packet rate is 1 pkt/s, 1600 interdomain packets will be generated. With a buffer size of 1000 packets, the packet loss rate is 1000/1600=0.67. In addition, the intradomain delivery ratio is only about 0.85. Thus, the effective delivery ratio for interdomain traffic when the packet rate is 1pkt/s is 0.67*0.85=0.53. The observed average intradomain packet delivery latency is about 800s. Thus, the average observed end-to-end delay is about 2*400 (on the average ferry visits two groups)+2*800s ~2400s.

For the RPGM model, with a ferry speed of 7.5m/s, the intergroup ferry visiting time is about 400s. Thus, the round trip ferry time is about 1600s. With a packet rate of 1 pkt/s, 1600 interdomain packets will be generated and hence a packet delivery ratio of 0.67 (1000/1600) is achieved by the ferry. However, the intradomain delivery ratio with the RPGM model is 0.89 which is higher than that for the VANET model (due to the different intragroup node movement characteristic). Thus, the effective packet delivery ratio for the RPGM model with a ferry speed of 7.5m/s and packet rate of 1pkt/s is 0.67*0.89=0.59. With a ferry speed of 15m/s, the intergroup ferry visiting time is only 220s and hence the delivery ratio achieved using the RPGM model with a packet rate of 1 pkt/s is much higher (0.71).

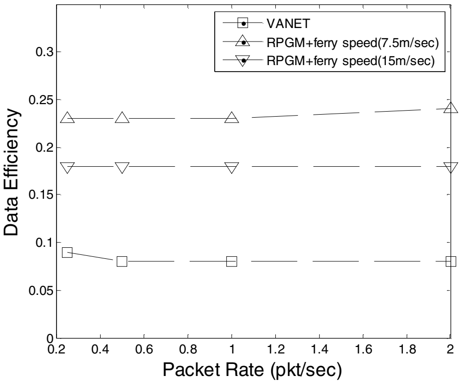
The average intradomain delay using the RPGM model is also smaller than that seen in the VANET model and hence the average e2e delay is smaller in the RPGM case compared to that seen in the VANET case. More transmissions need to be used in the VANET case due to more intermittent connectivity between nodes and hence the data efficiency seen in the VANET case is smaller than the values seen in the two RPGM cases.



(a) Delivery Ratio vs Pkt Rate



(b) Avg Msg Latency vs Pkt Rate



(c) Data Efficiency vs Pkt Rate

Figure 5: Delivery Performance of Different Mobility Models

Impact of Buffer Size

Next, we investigate the impact of different buffer size on the delivery performance when the VANET model is used. We use the same network model used in the previous set of experiments, but fix the multicast packet rate at 1 pkt/s. We vary the buffer size from 1000 to 2500 packets. We use the combined FBIM and EBMR2 scheme for the delivery of the multicast traffic. Our results are tabulated in Table 4.

Buffer Size	1000	1500	2000	2500
Delivery ratio	0.51	0.61	0.68	0.69
Delay	2301	2468	2725	2815
Data Efficiency	0.08	0.06	0.05	0.05

Table 4: Delivery Performance with Different Buffer Sizes

The above results indicate that the delivery ratio improves by 35% as the buffer size is increased from 1000 to 2500 packets. With increasing buffer size, more packets are stored. Hence, the average delay increases.

Impact of Different Numbers of Ferries

Next, we investigate the difference in the delivery performance using the VANET model for the case where a ferry only visits one outside group (resulting in each subnetwork having 3 ferries). In this experiment, we vary the packet rate from 0.25pkt/s to 2 pkt/s. Table 5(a) shows the results we get for the scenario with one ferry visiting all outside groups for each subnet while Table 5(b) shows the new results we get for the scenario with multiple ferries, each visiting just one outside group. The results indicate that when the packet rate is higher than 1 pkt/s, there is significant improvement in the delivery ratio using multiple ferries.

Pkt/sec	0.25	0.5	1	2
Delivery ratio	0.73	0.72	0.51	0.25
Delay	2231	2242	2301	2353
Data Efficiency	0.09	0.08	0.08	0.08

(a) Single ferry visiting all outside groups

Pkt/sec	0.25	0.5	1	2
Delivery ratio	0.73	0.72	0.68	0.47
Delay	1872	1923	1971	1993
Data Efficiency	0.08	0.07	0.07	0.07

(b) Multiple ferries, each visiting one outside group

Table 5: Comparison results with multiple ferries

Impact of Ferry Speed

Last but not least, we investigate the impact of ferry speed on the delivery performance of the interdomain multicast traffic. We use the network scenario with 10 groups of nodes moving according to the RPGM model for this set of experiments. We set the packet rate to be 2 pkt/s and vary the ferry speed from 15m/s to 30m/s. Table 6 tabulates the results we obtain. We see that the delivery ratio increases from 0.25 to 0.40 as the ferry speed varies from 15 m/s to 30m/s. The average end-to-end delay reduces from 2453s to 2012s as the ferry speed increases. The data efficiency remains the same since the ferry speed does not change the number of intradomain transmissions required for packet delivery once the interdomain traffic reaches its destination domain.

Ferry speed	15	20	25	30
Delivery ratio	0.25	0.31	0.35	0.40
Delay	2453	2267	2123	2012
Data Efficiency	0.08	0.08	0.08	0.08

Table 6: Delivery Performance with Different Ferry Speed.

VI. CONCLUDING REMARKS

In this paper, we have presented an integrated multicast delivery approach that consists of an efficient ferry-based interdomain multicast (FBIMR) scheme, and an encounter-based intradomain multicast routing scheme with redundancy (EBMR2) for disruption tolerant networks. Our FBIMR scheme assumes that one or more message ferries are deployed to deliver interdomain traffic from one domain to another. The EBMR2 scheme is used as the intradomain multicast routing scheme by a group leader to deliver messages it receives from a visiting ferry to its local multicast members. We conduct simulation studies to demonstrate that our integrated multicast delivery approach is scalable and can achieve high delivery ratio with reasonable data efficiency. Our simulation results also indicate that the combined FBIMR and EBMR2 scheme achieve better performance than the scheme we design in [12]. We also demonstrate that deploying more ferries provide better improvement in the interdomain multicast delivery performance than increasing the ferry speed of a single ferry.

In the near future, we hope to develop an analytical framework for estimating the ferry round trip time so that we can estimate the delivery ratio and end-to-end delay. In addition, we will look into the security design issue.

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