Robust Communications for Disconnected, Intermittent, Low-Bandwidth (DIL) Environments

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***Abstract*— Battlefield communications can be disrupted by a number of factors including environmental constraints, wireless dynamics and mobility, and both intentional and non-intentional interference. Robust, reliable, and efficient mechanisms are needed in such environments to ensure that critical data is delivered in the face of disruptions, intermittent connectivity, and low-bandwidth (DIL). In this paper, we examine a tiered approach to providing reliable communication in DIL environments. We model a tactical network scenario in which nodes in a low bandwidth loosely-connected ad-hoc network periodically send position/location information (PLI) messages to a shore base station. We utilize this scenario to quantify the differences in performance between a number of layered approaches that utilize mechanisms such as the Simplified Multicast Forwarding (SMF) protocol, the NACK-oriented Reliable Multicast (NORM), and Delay/Disruption Tolerant Networking (DTN) in mitigating the challenges of DIL environments. Our evaluation of the layered approaches considers metrics relevant to two broad classes of data: 'ephemeral' and 'persistent': ephemeral data (e.g. instantaneous position-location information of a node) has a relatively short lifetime and older data is obviated by newer data; by contrast, persistent data (e.g. exact mobility track of a node) has a longer useful lifetime and is not obviated by newer data. We examine the latency and staleness for ephemeral data and the message delivery ratio for persistent data. Our results show that SMF at the IP layer provides robust delivery to a single connected component of the network whereas NACKing and retransmission by NORM addresses short disruptions. For long-term disruptions, a DTN gossiping (i.e. anti-entropy) router can effectively bridge the gap between disconnected components. Our evaluation leverages the Common Open Research Emulator (CORE) tool and the mobility scripting tools from the Naval Research Laboratory (NRL).**

Keywords-DIL, SMF, NORM, DTN

I. INTRODUCTION

Tactical networking environments often exhibit disruptions, intermittent connectivity, and low bandwidth (DIL). These pose challenges to data communications that may be critical to the mission, such as distributing position/location information (PLI) or file transfers. To operate in DIL environments, mechanisms must be employed that can provide robustness against disruptions *and* reliable delivery of critical data in the most efficient manner. The Simplified Multicast Forwarding (SMF), the NACK-Oriented Reliable Multicast (NORM), and Delay/Disruption Tolerant Networking (DTN) are prominent mechanisms that can be utilized to face some of the challenges of DIL environments. In this paper we evaluate the performance of a tiered approach to reliability that uses these three mechanisms to combat short-, medium-, and long-term disruptions. Our evaluation shows that source-based multipoint relay (S-MPR) SMF at the IP layer provides robust delivery to a single connected component of the network but cannot bridge the gap between network partitions. The NACKing and retransmission of NORM on the other hand can effectively address short-term disruptions. For a long-term network partitions (or situations where no end-to-end path is possible), a gossiping DTN forwarder using an S-MPR SMF convergence layer provides an effective communication mechanism.

This paper is organized as follows. In Sections II and III we describe some mechanisms that can be utilized to mitigate various challenges of DIL environments. In Section IV, we detail the layered approaches we use. Section V and VI evaluate the performance of the layered approaches in DIL environments and discuss the results obtained. We conclude this paper is Section VII.

II. MITIGATING DIL EFFECTS

In this section, we describe some approaches to dealing with various aspects of DIL environments, primarily error-prone communications and temporary network partitions.

A. Simplified Multicast Forwarding (SMF)

SMF [1] is a framework for the efficient broadcast of IP packets, typically in the context of broadcast radio networks. In SMF, an algorithm is used to determine which nodes will be 'forwarders' responsible for relaying packets and which nodes are leaves of the distribution network. The set of forwarders is chosen so that all nodes are within one RF hop of a forwarder, and multicast packets are relayed by forwarders so that every packet is heard by every node. SMF itself does not include any reliability or retransmission mechanisms, focusing instead on the formation and maintenance of the forwarding set as the network topology evolves. Thus, the 'scope' of a multicast packet forwarded over SMF is the connected component of the transmitter.

B. Nack-Oriented Reliable Multicast (NORM)

NORM [2], [3] uses an underlying multicast service to send data and selective negative acknowledgements to elicit retransmission of missing data. NORM contains a number of mechanisms to improve efficiency such as a NACK backoff period to prevent NACK implosion at the source. Retransmissions are from the source to the original multicast group. NORM senders can be configured to hold on to data for a long time in case retransmissions are requested, but data delivery requires the underlying multicast delivery system to work. Thus, NORM requires contemporaneous end-to-end connectivity (at some point) between the source and the destinations.

C. Delay / Disruption Tolerant Networking (DTN)

DTN uses a long-term store-and-forward model to provide reliable data delivery even if the source and destination are never connected in the IP sense. To provide reliable delivery when end-to-end paths may not exist, DTN (and in particular, the Bundle Protocol (BP, [4] [5] [6])) supports a notion of 'data mules' that can physically carry information from one point in the network to another. The Bundle Protocol relies on an underlying transport mechanism to connect BP routers. Much of the routing research having to do with DTNs has focused on deterministic unicast routing (e.g. static routing, dtlsr) or probabilistic / epidemic routing (e.g. PRoPHET [7], RAPID [8]).

Here we choose to operate DTN above the transport layer and to use convergence layers to interface with the underlying IP-based network. A number of different convergence layers can be used, and TCP-based, UDP-based, and NORM-based convergence layers have all been developed for the DTN2 implementation. In this work we compare the performance of DTN using UDP-based convergence layers and IP Multicast with performance using NORM-based convergence layers (which themselves operate over IP multicast).

III. Extensions to DTN2 and the Bundle Protocol

In this section, we describe some extensions that we developed for the DTN2 BP implementation that can deal with some of the aspects of a DIL environment.

A. Gossiping Router

To allow broadcast messages to propagate past temporary network partitions we implemented a simple gossiping / anti-entropy router for the DTN2 BP implementation. When two DTN nodes that meet certain criteria encounter one another, they exchange their lists of messages to determine which messages are held by one end and not the other. Each end then sends the messages needed by the other. This is similar to but simpler than the MaxProp [9] routing protocol developed at the University of Massachusetts, Amherst.

Ideally the criteria for initiating the synchronization process would be that the neighbors were not previously part of the same connected component of the network. This information might be obtainable from a lower layer routing protocol such as OSPF, for example. For our case, we postulate networks where the underlying topology is changing rapidly enough that unicast routing protocols are not an option, so we instead leverage the neighbor discovery needed to support S-MPR SMF and declare that two nodes need to synchronize when they form a new link.

B. Superseding Bundle Extension Block

Many times, the broadcast data being disseminated in tactical environments is frequently updated, such as with PLI. In these cases, obtaining some subset of the data, often the more recent samples, in a timely manner can be more important than obtaining all of the data (i.e. ephemeral data). For disconnected and intermittently-connected networks, this can pose a problem for data mules. Each mule is in range of a connected component of the network for a limited period of time, and so they can only acquire or transmit a small amount of information. Even if there is sufficient connectivity, retaining all of the redundant information may tax the storage capabilities of the mule.

To reduce the number of redundant messages in the network, we implemented the capabilities of the Superseding Bundle Extension Block Informational Draft [10]. SBEB blocks allow the data sender to specify data which may be superseded by later data from the same sender. A number of different mechanisms are defined in [10] to identify obsoleted data. We use SBEB Type 0 blocks ("keep the most recent N messages with the same source and destination", with $N=1$). The effect of SBEB Type 0 blocks is similar to a set of drop-tail queues with one queue of size N for each source/destination pair. The unique aspect of bundles carrying SBEB blocks is that duplicate bundles are removed from the network, and so if too many bundles pile up at a data mule, redundant ones will be dropped. Figure 1 illustrates SBEB Type 0 operation for $N=2$. In the figure, bundles with different source/destination pairs represented as document icons with different colors and different leading letters. The numbers on each icon represent the creation times of the bundles.

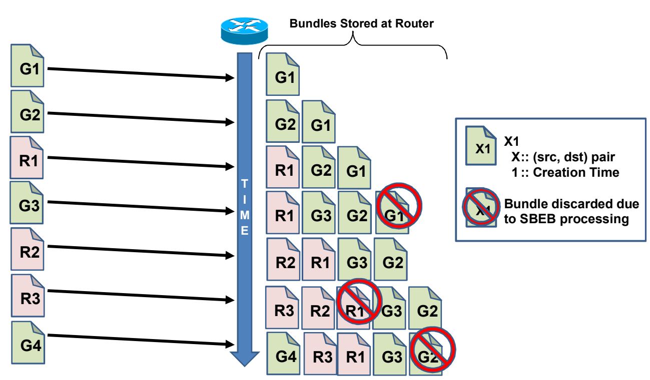

Figure 1. SBEB Operation

IV. A Layered Approach to DIL Communications

Each of the mechanisms described above addresses a particular aspect of DIL communications. SMF provides an efficient way to send a packet to every member of the network component connected to the source and provides for robust communications when the topology is changing quickly. A single NORM session will retransmit data or provide erasure repairing for objects to provide reliability, but still relies on end-to-end connectivity to the source. Thus, NORM can provide reliability across intermittent connectivity if there is occasionally end-to-end connectivity from source to destination. DTN supports communications when the network is intermittently partitioned and/or where the only connection through the network is due to data mules.

Table 1. Expected Performance Tradeoffs of the Layered Approaches Considered Under DIL Environments

	Efficiency within Connected Component	Robustness to Short-term Network Partitions	Robustness to Long-term Network Partitions
IP Unicast	✗	✗	✗
IP Multicast/SMF	✓	✗	✗
DTN/IP Multicast/SMF	✓	✗	✗
DTN/NORM/IP Multicast/SMF	✓	✓	✗
DTN Gossiping Router/IP Multicast/SMF	✓	✓	✓
DTN Gossiping Router & SBEB Extension/IP Multicast/SMF	✓	✓	✓

To consider the tradeoffs between the different approaches discussed in Sections II and III in different DIL environments, we compare the performance of the following layered approaches (also shown in Table 1):

- IP Unicast using NRL's OSPFv3 with MANET extensions [IP Unicast].
- IP Multicast using S-MPR SMF as the multicast forwarding scheme [*IP Multicast/SMF*].
- BP using a UDP multicast convergence layer with no routing at the BP layer [*DTN/IP Multicast/SMF*].
- BP using a NORM convergence layer operating over multicast IP and S-MPR SMF; no routing at the BP layer [*DTN/NORM/IP Multicast/SMF*].
- BP using the gossiping router using a UDP multicast convergence layer and S-MPR SMF as the multicast forwarding scheme [*DTN Gossiping Router/IP Multicast/SMF*].
- BP using the gossiping router with the SBEB extension, using a UDP multicast convergence layer and S-MPR SMF as the multicast forwarding scheme [*DTN Gossiping Router & SBEB Extension/IP Multicast/SMF*].

V. Scenario and Experiment Setup

A. Scenario

We model a tactical scenario involving four loosely-connected mobile ad-hoc networks and a shore base station. The mobile networks do not communicate directly with one another or the shore but instead rely on unmanned aerial vehicles (UAVs) with periodic orbits that occasionally connect nodes from the various mobile networks and/or the shore. For this work we do not artificially constrain the available storage at the data mules, though we do track the storage use to assess the benefits of the SBEB extension. Within each of the mobile networks, nodes move randomly within a prescribed box.

We used a simple distance-based threshold link model for connectivity among nodes, which we set to be 275m. The nominal link data rates for the MANET groups as well as the UAVs were 75Kbps. The scenario is depicted in Figure 2.

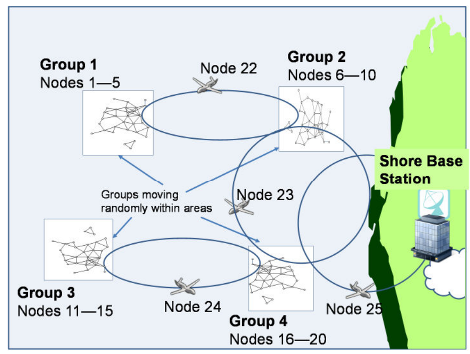

Figure 2. Scenario with Four Mobile Networks Connected by UAVs.

We used the Linux version of the Common Open Research Emulator (CORE) emulator [11] to emulate the scenario. The NRL Mobile Network Modeling (MNM) Tools [12] were used to generate the mobility scripts for the nodes.

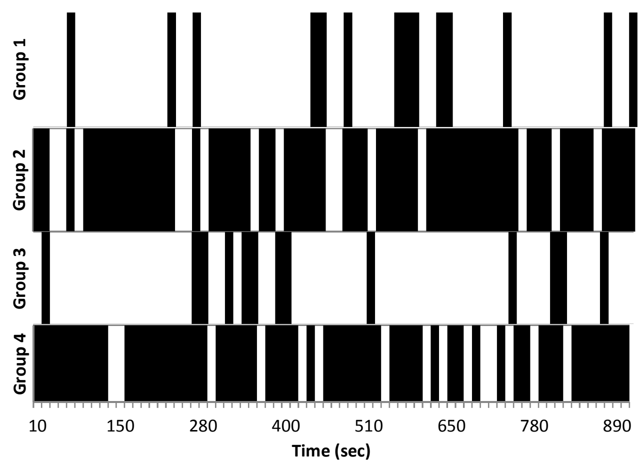

Figure 3. Timelines for Group Connectivity to the Shore Base Station.

B. End-to-End Connectivity

An important aspect of the scenario is the presence or absence of end-to-end connectivity. To make meaningful comparisons between end-to-end-based (e.g. IP Multicast, NORM) and DTN-based delivery methods, there must be at least some end-to-end connectivity between all communicating nodes. In the tactical scenario described above, nodes within groups 1 and 3 had end-to-end connectivity to the shore base station about 20% of the time while nodes within groups 2 and 4 had end-to-end connectivity about 80% of the time. Figure 3 shows a timeline of the group connectivity to the shore base station. Black bars indicate end-to-end connectivity between at least one member of the group and the shore; white spaces indicate lack of connectivity.

C. Test Data

We consider two types of data: ephemeral and persistent. Ephemeral data is data of transient utility and is transmitted frequently. More recently generated ephemeral data is presumed to be more useful than older data, and some loss is assumed to be tolerable (e.g. instantaneous node location). Persistent data on the other hand is 'important' and must be delivered to its destinations (e.g. exact mobility track of a node).

To measure a system's ability to deliver both types of messages, we use mock PLI messages sent every 10s by each of the MANET nodes (the UAVs do not send PLI messages). Each one of the layered approaches described earlier is used to transmit the PLI messages independently. All the DTN-based approaches use a lifetime of 60s on the PLI messages generated. The shore base station logs the messages it receives as well as the receipt times in order to compare the performance of the layered approaches. The mobility scenario was run for 1000s (i.e. each node generated 100 PLI messages), then for another 100s to allow messages to clear the system before terminating the emulation.

D. Comparison Metrics

We use the following metrics to compare the performance of the different layered approaches considered:

- *PLI message delivery ratio*: This metric assesses the ability of an approach to deliver PLI messages from nodes to the shore base station. It reflects the performance of an approach with respect to persistent data. A good approach will succeed in delivering the majority of the data (i.e. close to 100% of PLI messages delivered).
- *PLI message latency*: This metric assesses the latency in delivering PLI messages to the shore base station. We calculate latency as the elapsed time between when a PLI message is generated by a node to the time it is received at the shore base station. It reflects the performance of an approach with respect to ephemeral data. A good approach will have an average message delivery latency that is less than the lifetime of the ephemeral data (i.e. the window of time in which this data is of value).
- *PLI message staleness*: This metric assesses the length of the window of time between received PLI messages. A small message delivery latency might misleadingly indicate good performance with respect to ephemeral data. However, if the delivery ratio is small then the data held by the shore base station will tend to be old. Staleness captures that by reporting the elapsed time since the last PLI message from each node was received at the shore base station. It reflects the performance of an approach with respect to ephemeral data. A good approach will have an average message staleness that is smaller than the lifetime of the ephemeral data (i.e. the window of time in which this data is of value).
- *Inter-group connectivity*: This metric is applicable to multicast approaches only. In these approaches, each node will record all PLI messages that it overhears from all other nodes. We can then use this information to calculate the PLI message delivery ratio across networks, which reflects the ability of different mobile networks to communicate with one another. A good approach will have a high PLI message delivery ratio from all other groups.

VI. RESULTS

In this section, we discuss the results of our performance test for each of the layered approaches considered. All our results were averaged over 30 runs per layered approach and we note the 95% confidence interval for all our results.

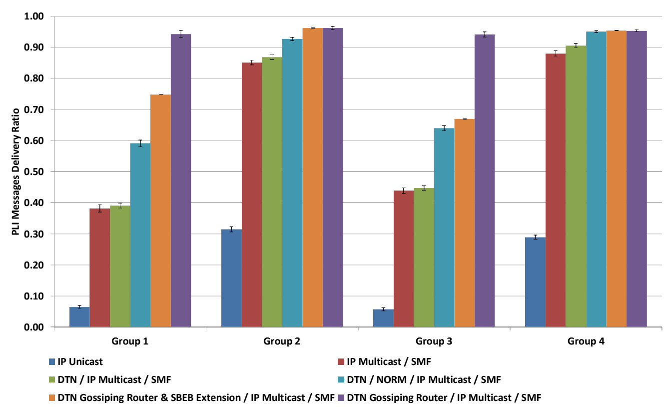

Figure 4. Ratio of messages delivered by group and delivery method.

A. PLI Message Delivery Ratio

Figure 4 compares the PLI message delivery ratios of all six layered approaches as calculated by the shore base station. Each stacked set of columns represents the average PLI message delivery ratios for a given group (shown in Figure 2) using one of the layered approaches. Each layered approach is marked with a different color. The Figure shows poor performance for the *IP Unicast* approach (less than 0.1 message delivery ratio for groups 1 and 3 and about 0.3 for groups 2 and 4). The dynamics of the network challenges the ability of the unicast routing protocol (i.e. OSPFv3) to form a stable end-to-end route from any given node to the shore base station, which results in loss of PLI messages. On other hand, both *IP Multicast/SMF* and *DTN/IP Multicast/SMF* approaches yield better performance than *IP Unicast* (about 0.4 message delivery ratio for groups 1 and 3 and about 0.85 for groups 2 and 4). Both will allow delivery of PLI messages within the connected network component of the sender. *DTN/IP Multicast/SMF* is performing similar to *IP Multicast/SMF* since we are not employing any routing at the BP layer (a unicast routing protocol at the BP layer will not converge for the same reasons that OSPFv3 won't converge in the IP Unicast approach). When NORM is employed, its NACKing and retransmission mechanism allow for more reliability in message delivery (about 0.6 message delivery ratio for groups 1 and 3 and about 0.95 for groups 2 and 4). PLI messages that were missed by the shore base station when the network was partitioned will be NACKed when an end-to-end connection to the source node is available. Source nodes will then attempt to retransmit the missed PLI messages. Superior to all is the delivery ratio of the *DTN Gossiping Router/IP Multicast/SMF* (about 0.95 message delivery ratio for all groups). The gossiping mechanism ensures that messages are delivered across network partitions without the need for an end-to-end connection to the shore base station to ever be present.

The respective PLI message delivery ratios for groups 2 and 4 is much better in than that of groups 1 and 3 in *IP / Unicast*, *IP Multicast/SMF*, *DTN/IP Multicast/SMF*, and *DTN/NORM/IP Multicast/SMF* approaches, as shown in Figure 4. This is intuitive since groups 1 and 3 need at least two UAVs to have an end-to-end connection to the shore base station, while groups 2 and 4 only need one. The *DTN Gossiping Router/IP Multicast/SMF* approach on the hand has consistent message delivery ratio for all 4 groups.

Figure 4 also shows results for the *DTN Gossiping Router & SBEB Extension/IP Multicast/SMF* approach. When the SBEB extension is employed the deliver ratio is lower than when it is not. The SBEB extension is meant to reduce the percentage of messages delivered by discarding messages that the *application* indicated as being redundant (i.e. 'ephemeral' data). This will guarantee that only the latest information will be delivered to the *application*.

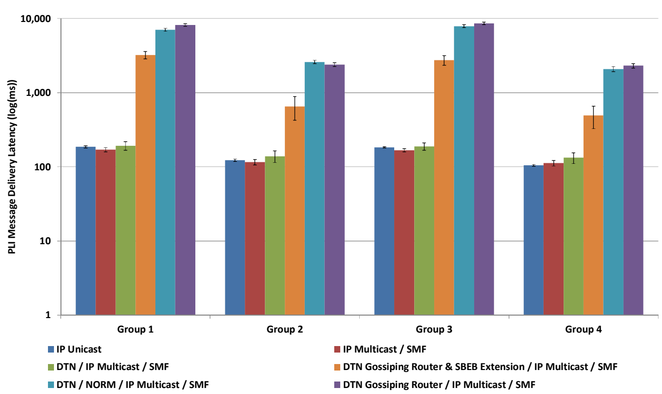

Figure 5. Message delivery latencies by group and delivery method for PLI messages delivered to the shore base station.

B. *PLI Message Latency and Staleness*

Figure 5 shows the average message delivery latencies for PLI messages from the different groups to the shore base station using the different layered approaches. From the Figure, we see that the delivery latencies of the *IP Unicast*, *IP Multicast/SMF*, and *DTN/IP Multicast/SMF* approaches are lower than the latencies for the other approaches. This must be the case since using these methods messages can only be delivered across connected portions of the network. The reliable mechanisms, particularly DTN using the gossiping router and NORM, increase reliability by being robust against having to wait for connectivity to become available. This increases the latency of message deliver for both approaches.

Figure 6 shows the staleness of information received at the shore base station. This measure of effectiveness does not penalize SBEB for removing redundant information by showing the average 'staleness' of messages from the various groups. It is clear that the staleness of information when using SBEB is lower by about 23% than when it is not used. Moreover, the Figure also highlights the fact that while the *IP Unicast* approach achieves similar latency to that of *IP Multicast/SMF* and *DTN/IP Multicast/SMF* approaches, its lower PLI message delivery ratio causes staleness of the PLI information at the shore base station.

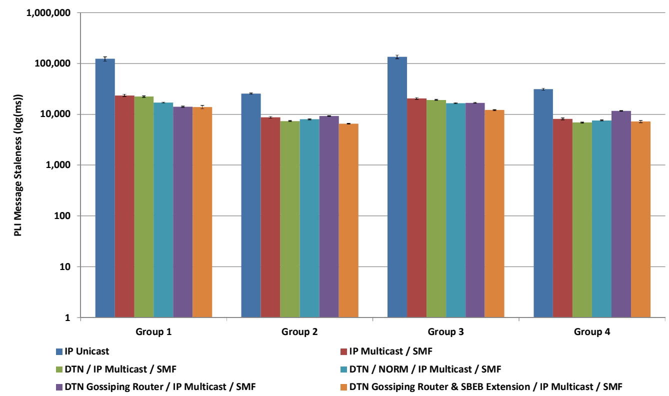

Figure 6. Data 'staleness' by group and delivery method.

C. *Inter-group Connectivity*

Figure 7 shows the inter-group PLI message delivery ratios (i.e. PLI messages received from all other groups) in the multicast scenarios. All layered approaches seem to perform well delivering almost all PLI messages within the sender's own group. This attributed to the operation of the S-MPR SMF mechanism. Inter-group message delivery ratios are much lower in comparison for all scenarios with the exception of the *DTN Gossiping Router/IP Multicast/SMF*, which yields about 0.95 inter-group PLI message delivery ratios.

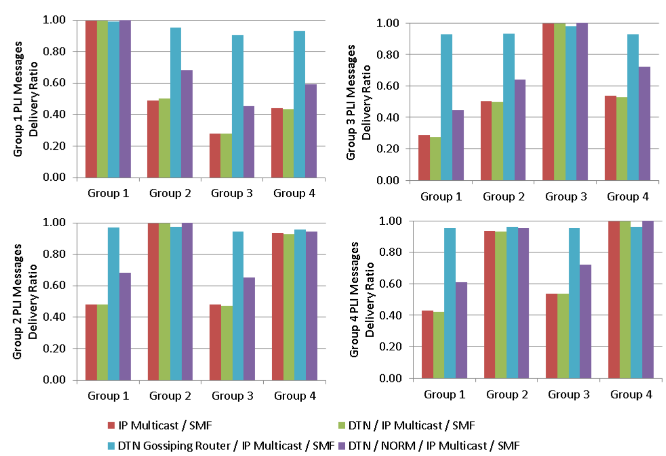

Figure 7. Inter-group message delivery ratios in the multicast scenarios.

D. *Tradeoffs of the DTN Gossiping Router*

The DTN Gossiping router is meant to operate under extreme environments where end-to-end connectivity may never occur. To illustrate this point, we moved group 3 south west of it location shown in Figure 2 so that the group was intermittently connected to the UAV "*node 24*" once every 20 seconds but an end-to-end connectivity to the base station was never possible. None of the layered approaches, including the one using NORM was able to deliver a single PLI message from group 3 to the shore base station. The DTN Gossiping Router/IP Multicast/SMF on the other hand was able to deliver around 90% of the PLI messages from the group with a latency of about 30s and a staleness of about 39s.

The tradeoff to the DTN Gossiping router's robustness against long-term network partitions is storage overhead. Nodes will have to store bundles that they overhear being forwarded (by SMF) from other nodes. To measure the overhead of storage, we observed the average number of pending bundles within each group. Nodes in groups 2 and 4 hold a higher number of pending bundles (about 110) since they are in the path to every PLI message. Nodes in groups 1 and 3 as well as the UAVs hold an average of 96 pending bundles at any time instance.

Nevertheless, employing the SBEB mechanisms significantly reduces the average number of stored bundles (which reduces the overhead for both data transfers and synchronization of the DTN Gossiping Router).

VII. Conclusions and Future Work

By combining the mechanisms described above: Simplified Multicast Forwarding, NORM, and DTN, we can construct a network infrastructure providing efficient, optionally-reliable data delivery in disrupted, intermittently-connected, and low-bandwidth environments. SMF provides robust data dissemination within a connected network component through multi-path forwarding and exploiting the broadcast nature of radio channels; NORM provides retransmissions and erasure coding to recover from short-term disruptions such as fading; and DTN provides resiliency against long-term outages and cases where the network is never contemporaneously end-to-end connected. A DTN Gossiping Router has shown tremendous robustness to long-term network partitions at the expense of additional storage overhead on the nodes. However, employing the SBEB mechanism reduces that overhead significantly at the expense of reduced message delivery ratio (which might be OK if the data is of the 'ephemeral' type).

The threshold link model used here fails to capture much of the dynamics we expect to see out of real mobile networks. Real networks with more short-term outages / disconnections should benefit more from NORM's retransmissions and/or proactive erasure correction. To examine this we plan to implement a Markov on-off process for links within the CORE emulator to examine more sophisticated link failure models and mobility-induced disruption.

The DTN2 BP implementation is intended as a pedagogical implementation that is easy to understand, extend, and experiment with. DTN2's event processing machinery is not particularly well-suited to environments where there are many changes per second such as links coming up and down, bundles being transmitted, etc. Some mechanism for improving the event processing needs to be explored, such as prioritizing events so that 'control'-related events such as link establishment / termination are processed before data events such as bundle transmissions.

A study of the sensitivity of the various metrics to the message creation rate and / or lifetime should show additional benefits of SBEB. We noticed during our emulations that increasing the message creation rate to one message every five seconds put a significant load on the system. Because SBEB reduces the total number of messages in the system, it should help reduce this load somewhat.

The gossiping router synchronization procedures are currently executed by two nodes whenever a new link is formed between them. A number of optimizations are possible in determining when exactly to synchronize. For example, two nodes might only synchronize if they were previously not 2-hop neighbors (information that the SMF associated neighbor discovery process may already have). Ideally, synchronization would only occur between two nodes that were not (prior to forming a link between them) in the same connected component. To take full advantage of such a synchronization mechanism, we need a highly reliable way of disseminating information to all nodes of a connected component. We believe that the NORM / IP Multicast/SMF portion of the stack will provide sufficient reliability, but need to investigate this component separately.

Acknowledgment

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