

# Delay Tolerant Network Routing: Beyond Epidemic Routing

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**Abstract**— In this paper, we identify two distinct classes of routing algorithms for Delay or Disruption Tolerant Networks (DTN). The purpose of this classification is to clearly delineate the assumptions they work under and to facilitate mapping of applications to these algorithms. Algorithms based on opportunistic contact and some variant of epidemic routing use minimal topology knowledge and the most resources due to replication. The island-based algorithms find routes between connected islands and are closer to real applications such as tactical military networks. The general consensus is that there is no single routing solution that will minimize delay at the same maximizing throughput for DTNs. Majority of the algorithms assume non-standard and diverse scenarios which makes comparative evaluation difficult. Mapping applications to algorithms also poses a problem as many of the known applications do not match in scale the rigor of the proposed algorithms. Further efforts in standardization and verifiable evaluation using application context are the way forward.

**Keywords**—Delay Tolerant Routing, Epidemic Routing, Store and Forward Networks

## I. INTRODUCTION

A DTN is an emerging class of networks that defines a new approach and a framework to provide networked services in non-TCP/IP networks, sometimes also referred to as “challenged” networks [1]. Some unique challenges arise as we move away from the underlying assumptions for traditional TCP/IP-based networks. To operate TCP protocol, there must be an end-to-end path between the source and the destination and the round trip delays must be small enough that there can be a “conversation” about the data transfer between the source and the destination. Neither of these assumptions is valid in a DTN -- intermittent connectivity makes it difficult to guarantee an end-to-end path for an ongoing data transfer and long round trip delays make it impossible to provide timely acknowledgements and retransmissions. DTN architecture is designed to provide support for message-based asynchronous communications over networks prone to frequent disconnections, long and variable delays, and bandwidth limitations. In addition, DTN devices may have resource limitations such as storage and power. The reference implementation in [1] describes DTN as an overlay network that operates over disparate underlying network technologies

providing routing services using store and forward approach over intermittent network connectivity using a message abstraction called bundles.

There are a number of applications both military and civilian that can benefit from DTN technology (See Table 1). The US Marine Corps project CONDOR (C2 On-the-move Network Digital Over-the-horizon Relay) is one such application where DTN specific ideas are being tested on prototypes [2,3]. CONDOR and other projects in Table 1 represent DTN-type environment where moving data around is a problem using conventional networks because of longer lasting disconnections and dynamic topology within the network. For instance, the wildlife tracking system, ZebraNet can not be operated as a multi-hop wireless sensor network and requires a different routing mechanism.

TABLE I. DTN PROJECTS/PROTOTYPES

Project/Prototype	Description
CONDOR [2]	US MARINE Corps Project – C2 On-the-move Network Digital Over-the-horizon Relay
DakNet [4]	Connecting rural villages in India using kiosks and buses
ZebraNet [5]	Wildlife tracking system using Zebras in Africa
UMassDieselNet [6]	DTN Testbed using 40 buses on University of Massachusetts Campus
PA-UWNT [7]	The Philadelphia Area Urban Wireless Network Testbed for first responders

## II. CHALLENGES IN DTN ROUTING

The primary challenge for routing in DTNs is the dynamic topology of the network due to intermittent connectivity. DTN topology may consist of static and mobile nodes. The links between pairs of static nodes could be up or down, for instance through intentional duty cycling to conserve resources. If mobile nodes are involved, network topology changes as nodes move. In such a situation the link connectivity between pairs of nodes is brought about when they come into range of each other. Therefore, mobility causes intermittent connectivity. This by itself is not a problem if we can detect synchronous

multi-hop paths between a source and a destination as we do in MANETs. In a DTN however, that is not the case because there is no assumption regarding node density to enable multi-hop paths.

The extent of topology knowledge is critical to the design of a routing algorithm. At one extreme, opportunistic contact between pairs of nodes is the only way for possible eventual delivery of data. Much of routing decision needs to be made using minimal topology knowledge, the extent of which could be that each node can detect only its neighbors and is unaware of the number and location of other nodes in the topology. At the other extreme, scheduled contact between nodes of known topology may lead to a possible asynchronous path between nodes for an eventual delivery. The challenge is to design routing algorithms that will maximize delivery ratio and minimize delay where possible.

### III. EXISTING ALGORITHMS

We identify two distinct classes among the proposed DTN routing algorithms:

The first class of algorithms is the epidemic routing-based algorithms that make the most use of opportunistic contact. For these algorithms the required topology knowledge is minimal. Uncontrolled mobility is an essential feature giving rise to opportunistic contact between mobile nodes. Table 2 provides a feature summary for the algorithms in this class.

With minimal or no topology knowledge the simplest delivery scheme is to copy the message to each node that the source and its relays come in contact with – this is the basic idea behind epidemic routing. This will result in a maximum of  $(n-1)$  copies in a network of size  $n$  nodes, more if we allow multiple copies to exist within the same node. As is evident, this strategy consumes the most resources in a generally resource deprived network environment. Despite having a high per packet delivery probability and the lowest delay, the non-scalable nature of this solution demands limitations on replication. Variants of epidemic routing adopt limited replication trading delay for capacity. One of the following two strategies is used to limit replication in the existing algorithms: 1) fix the number of copies and disperse on contact with distinct relay nodes; 2) use historical encounter-based metrics to decide whether to copy the message on contact.

The second class of algorithms uses topology knowledge and controlled mobility – all prototypes mentioned in Table 1 operate under these assumptions. The topology generally consists of islands of nodes locally well connected but intermittently connected across islands. A special node called a ferry is employed which moves around the deployed area collecting data among islands of connected nodes. In a majority of these algorithms, topology knowledge is assumed to be not a limiting factor and therefore, single copy forwarding strategy can be adopted. Given approximate or precise node location, the routing problem deals with evaluating the effect of ferry movement on delay in data delivery and collection. Sparse sensor networks, tactical military networks are some example applications. Storage and other resources such as power feature predominantly as constraints in this class of algorithms.

A feature summary is provided in Table 3 for some of the algorithms in this class.

### IV. DISCUSSION

Most of the existing algorithms mentioned in Tables 2 & 3, have the following structure: contact opportunities occur based on certain mobility pattern; messages are selected for transfer using some decision rule; messages are dropped based on some logic when using finite buffers; messages are either replicated or a single or limited number of copies is forwarded on contact; acknowledgements are flooded to purge delivered packets in some of the algorithms.

Overhead: The comparison overhead for message selection during the transfer phase can be non-negligible. The prevailing condition in a DTN is that the data transmission demand is always more than the capacity which makes contact duration a scarce resource. The goal in that case should be to maximize the utility of contact duration in actual message transfers, and meta-data exchange should be minimized. The computational needs must also be kept to a minimum.

Limited Replication: Limited replication has been consistently used in ad hoc research community to achieve scalability. Many of the DTN routing algorithms adopt limited copy transmissions with the associated trade-off between delay and capacity. Limiting the replication will also decrease the per packet delivery probability just because of the reduced number of possible routes. Many of the DTN routing algorithms try to incorporate intelligence derived from encounter history in selecting the message recipient to increase that probability. Single copy transmission option does not work well in DTN scenarios where topology knowledge is non-existent or outdated.

Evaluation: Algorithms in each of the two classes represent varied application scenarios. Because of the non-standard operating conditions each models, it is difficult to evaluate the merits of one algorithm in relation to others. For instance, it is not possible to rank order the relative performance of algorithms like Spray and Wait, SWIM or PROPHET. Similar problem exists for the controlled mobility algorithms – each represents a different scenario and mapping it to a known DTN application is not easy. Evaluation methodology also differs – number of transmissions and delay are the metrics used in Spray and Wait where it is shown to perform better than other flooding-based or utility-based algorithms; in SWIM, the time to deliver each message is measured in the simulation and compared to analytical results. PROPHET is compared to Epidemic using delivery rate and delay as the metrics.

### V. FUTURE DIRECTIONS

Some unanswered questions remain as we survey the field of DTN routing algorithms which are:

*Given a network size and mobility pattern, how can we quantify contact opportunities and durations?* An associated question is, for a given workload, what fraction of that contact duration do we spend in overhead? For instance, in Epidemic routing, the message summary vectors are exchanged and compared to select the messages for transfer – this overhead amounts to a worst-case overhead of  $O(n^2)$  for  $n$  messages at

each node. In other algorithms, there is also the computational overhead in processing the delivery predictability factor for the node in question before exchanging the messages. From existing discussions on the algorithms, it is not clear what fraction of the contact times on average is spent on such overhead. Improved methods in this regard will result in efficient use of the bandwidth and increased throughput assuming that transmission demand is more than contact duration. In general, quantifying the relationship between network size in terms of node density and contact opportunities and durations and their underlying dependence on the mobility pattern are all open problems.

*How much replication is too much or too little?* Spray and Wait algorithm provides some answers to the number of replicated copies needed to achieve a desired expected delay. At the two ends of the spectrum are epidemic and single-copy. In between are other algorithms but it is not clear from existing evaluation, what their relative performance is. We need a standard methodology and metrics and a well defined network environment to conduct a comparative evaluation of algorithms.

*How do we accurately model mobility before we exploit it for forwarding purposes?* Many of the algorithms evaluate a potential recipient based on their encounter history. But that encounter history is only as accurate as the assumed mobility pattern. For a realistic evaluation, this pattern has to mirror the underlying application scenario.

*How efficiently should in-network storage be managed?* Storage is a constraint in DTN routing and yet, many of the algorithms do not consistently treat it as such. Messages may get dropped because of buffer overflows on intermediate nodes reducing overall network utilization. Integrating storage into routing may in fact reduce congestion in DTNs by load balancing network storage and increased throughput. In addition, reclaiming storage from delivered and undeliverable messages is also a good idea. Many of the algorithms use expiration time or hop count to purge undeliverable messages. In some, acknowledgements are flooded so that redundant copies of delivered messages can be destroyed. Despite these measures, DTN routing using store and forward approach requires more efficient network storage management and the challenge is to see how.

Protocol development for routing in MANETs was made simple by following the end-to-end argument. However, that task is more complicated in DTN routing because of the absence of a standard network environment; because of the diversity of applications and mobility models that may have to be tailored to specific application scenarios. While many of the current DTN applications do not match in scale the rigor of proposed algorithms, they provide the context for protocol development. While monolithic development of protocols for DTN environment may not be possible some effort in standardization and verifiable evaluation using application context is needed.

## VI. CONCLUSION

In this paper, we classify DTN routing algorithms based on mobility pattern and topology knowledge. The epidemic routing based algorithms assume minimal or no knowledge of topology and the individual nodes move in uncontrolled manner resulting in opportunistic contact for data delivery. The island-based algorithms are based on intermittent connectivity among islands of connected nodes and use topology knowledge and controlled mobility. While many of the known DTN applications do not map well to the epidemic-based algorithms, the island-based algorithms hold promise. The known applications also do not match in scale the rigor of proposed algorithms, but they provide some measure of authenticity and verifiability. A study of the existing algorithms point to a need for well defined network environments with verifiable comparative evaluation of these algorithms.

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TABLE II. UNCONTROLLED MOBILITY ALGORITHMS – FEATURE SUMMARY

Project/Algorithm	Node Type & Mobility	Contact Type	Topology Awareness	Traffic
Epidemic [8]	MANET w/partition & Random	Opportunistic, random pairwise exchange of messages	None One hop neighbors, unique node ids	Random source and destination pairs
PROPHET [11]	MANET w/partition & Random and Community-based	Opportunistic, message exchange based on delivery predictability (using encounters)	None One hop neighbors, unique node ids	Random source and destination pairs
Spray and Wait [9]	MANET w/partition & Random	Opportunistic, message copy forwarding based on a specific spraying heuristic.	Partial (Number of nodes in the network can be estimated to find optimal spray copies)	Random source and destination pairs
SWIM [10]	Static and mobile infostations and mobile nodes & Random	Opportunistic between node to node and node to infostation	None Neighbor discovery	Node to infostation via another node or directly

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Data MULES[12]	Static sensor nodes and mobile collector nodes Mule mobility: Fixed and Poisson inter-arrival time, Random	Opportunistic if Mules move randomly and by route design if Poisson or deterministic	Complete if Mule mobility is not random; sensor nodes location is needed	Sensor to Mule (and Mule to access point)
Message Ferry [13]	Static nodes and mobile ferries Controlled mobility	By route design	Complete	Node to node via ferry, ferry to ferry
DTMN (Harras & Almeroth) [15]	Mobile nodes self configured as clusters/regions; within a region there is an end-to-end path & Random	Scheduled messenger type nodes moving among regions; GPS enabled node in a region makes its location known to messengers	Partial – region location is known	Node to node and to messenger nodes
EDIFY(Lehigh) [14]	Mobile regular nodes and mobile ferry	Predicted (Ferry routes based on earliest deadline for delivery)	Partial – ferry knows node location	Node to ferry