A Framework for Simulation Analysis of Delay Tolerant Routing Protocols

Sathya Narayanan, Eric McDonald
Computer Science and Information Technology Program
California State University, Monterey Bay
Seaside, CA 93955.
Email: snarayanan, ermcdonald@csumb.edu

Geoffrey G. Xie
Department of Computer Science
Naval Postgraduate School
Monterey, CA 93943.
Email: xie@nps.edu

***Abstract*—A variety of network deployments in disaster recovery, fire fighting and military scenarios create networks that do not form a connected network all the time. In such scenarios, paths between a source and destination may be created over time when nodes encounter each other due to node mobility. Many routing algorithms that can route messages in such delay-tolerant networking (DTN) settings have been proposed. Each of these proposals presents simulation and/or analytical results to demonstrate improved performance in comparison with other known protocols. This paper proposes a common framework that defines multiple important components through which performance of these protocols can be compared using simulation experiments. This framework includes performance metrics that can be used for comparison, simulation environment, new mobility models and results in organizing the various known protocols based on their ability to predict a path. In a case study using the framework, we demonstrate how the predictive ability of PROPHET may or may not result in significant performance gains, depending on the mobility model.**

I. Introduction

Delay tolerant routing algorithms find end-to-end paths for messages to travel in scenarios with devices forming a disconnected network. In such a network, a path between the source and destination may not exist when a message leaves the source, requiring the routing algorithm to identify a path over time as the devices move and encounter each other. Since the message will be buffered at the devices as the devices move along, the protocol must be tolerant of higher end-to-end message delay than expected in traditional networking scenarios.

Developing routing algorithms for such dynamic scenarios is a challenging problem with a few well known solutions proposed in the literature. However, these solutions have not been evaluated in a systematic manner that would lead to the insights necessary for framing the full design space. In this paper, we present a framework to conduct simulation experiments on the performance of these protocols along with results from simulation study of two prominent routing protocols that occupy the two ends of the opportunistic to predictive spectrum developed by the proposed framework.

II. Literature survey

The simplest DTN routing algorithm proposed in [1], Epidemic, is also the most greedy routing algorithm as it will always find the first possible path for a message between a given source and destination as long as the message doesn't get dropped due to queue overflow. Epidemic routing is discussed further in subsection II-A.

[2] proposes a dynamic data delivery scheme for delay/fault tolerant mobile sensor networks (DFT-MSN) and develops a simplified queuing model based on Jackson network theory along with simulation study. The proposed scheme relies on an estimated nodal delivery probability based on the number of encounters the node had over a given time window. This delivery probability is different from the delivery probability of PROPHET, proposed in [3], which estimates the probability of message delivery to a given destination. PROPHET is discussed in detail later in subsection II-B.

Reference [4] discusses the performance of a proposed protocol, Look Ahead Routing and Message System (ALARMS), compared to three existing routing protocols: epidemic, spray-and-wait, and spray-and-focus. The simulations were run using an extended version of the ONE simulator. The results indicate that ALARMS achieves a better delivery ratio and shorter delivery delay with much lower overhead as it relies on the knowledge of predefined routes for the mobile nodes in the network. [5] proposes a cluster-based routing protocol. This protocol operates by clustering nodes with similar mobility patterns and allowing only direct transmissions within clusters. Gateways nodes are designated to take on the responsibility of routing between clusters.

A. *Epidemic routing protocol*

Epidemic routing relies on forwarding messages to every encountered node, spreading the message through the network like a disease spreads through the population. If the network is not congested, Epidemic will find the shortest/fastest path between a given source-destination pair at a high cost of too many duplicate messages in the network. In environments with multiple messages being generated at the different sources on the network, Epidemic will lead to congestion as it is aggressive in making duplicates.

B. *PROPHET protocol*

Probabilistic Routing Protocol using History of Encounters and Transitivity (PROPHET) is another type of routing pro-

978-1-4673-1881-5/12/$31.00 ©2012 IEEE

Hop Limit \ Forwarding Condition	**Pe > Pp** Pe is the P value for the encountered node and Pp is the P value of the previous node to which the message was forwarded	**Pe > Ps** Pe is the P value of the encountered node and Ps is the P value of self, the node making the forward decision
2 Hop Limit -Message source is allowed to forward to intermediary nodes if the forwarding condition is met -Intermediary nodes can only deliver to destination	**Type 1**	**Type 2**
No Hop Limit -Message source and intermediary nodes are allowed to forward to other nodes if the forwarding condition is met.	**Type 3**	**Type 4**

Fig. 1. PROPHET Forwarding Decision Algorithms

tocol proposed for a DTN environment. PROPHET calculates which nodes have the higher probability of delivering data to the destination node based on the history of encounters among the various nodes in the network [3]. Once this probability (p-value) is calculated, different criteria can be used for a node to decide whether to forward a message to a node it just encountered.

III. Research methodology

The proposed framework aims to organize the known DTN routing protocols in a spectrum ranging from aggressive to predictive based on a metric that quantifies the predictive ability of various protocols. The rest of the paper describes the framework and how it can used to analyze the performance of DTN routing protocols with a focus on the two prominent DTN routing protocols, Epidemic and PROPHET, providing the extreme cases, to gain insights into the performance of DTN systems. The following research steps were used to refine the framework:

- Develop and define specific variations of Epidemic and PROPHET algorithms that will clearly fit into the proposed aggressive to predictive spectrum.
- Define the performance metrics that will be collected through the simulation experiments.
- Define the simulation setup and configuration parameters.
- Conduct simulation experiments and collect data on the performance metrics.
- Analyze results and repeat experiments.

A. *Proposed protocol variations for study*

We propose variations of Epidemic and PROPHET to gain insights into the behavior of the protocols and identify fundamental properties that impact the performance of DTN networks. Epidemic routing was extended to support probabilistic behavior by defining a parameter ‘q’ (the protocol is now referred to as q-Epidemic). Whether a message exchange between two encountered nodes happens or not is based on the probability value q. Obviously, with q=1, q-Epidemic behaves exactly same as the original epidemic protocol, and with lower values for q, flooding of messages through the network is throttled. By controlling the value of q the protocol behavior becomes less aggressive.

This paper proposes four ways by which the PROPHET model can be used to decide the best next hop node for a given message. The four algorithms are represented in Fig.1. PROPHET types 1 and 2 are restricted to a two hop limit, meaning that intermediary nodes can only deliver the message to the destination and not to each other. PROPHET types 3 and 4 do not have a hop limit and will use as many intermediary nodes as needed. PROPHET types 1 and 3 only forward a message to an encountered node if the p value of the encountered node is greater than the p value of the node to which the message was previously forwarded. PROPHET types 2 and 4 only forward a message if the p value of the encountered node is greater than the p value of the node making the decision.

B. *Performance metrics*

The three main performance metrics collected in this study are:

- **End-to-end message latency** (l)**:** This metric measures the time between message creation at the source and message delivery at the destination.
- **Number of duplicate messages** (d)**:** This metric measures the number of duplicate messages in the queues of other nodes when the first instance of that message is delivered.
- **Delivery percentage:** This metric indicates the percentage of message successfully delivered to their respective destination at the end of the simulation.

The main objective of routing in DTN is to reduce the end-to-end delay of messages. But, the number of duplicate messages generated should also be studied to better understand the overall cost of a protocol in terms of memory and bandwidth. The number of duplicate messages may also impact the end-to-end delay of future messages by clogging the outgoing queues in nodes in the network. A protocol’s delivery percentage must also be monitored to ensure it is delivering a significant amount of the messages it generates. Throughout the course of our experimentation aggressive protocols demonstrated lower latency, a higher number of duplicate messages, and generally a higher delivery percentage in scenarios with low message generation rate. However, in scenarios with higher message rate, the high number of duplicate messages often lead to congestion in queues resulting in higher latencies and lower delivery percentages which needs to be taken into consideration in the choice of DTN routing protocols.

We propose the use of a new metric, we call predictive ability δ, defined with respect to the performance of simple Epidemic routing - this will be the ratio of end-to-end delay times number of duplicate messages of Epidemic routing over end-to-end delay times number of duplicate messages of a given protocol. If the average end-to-end delay of Epidemic is

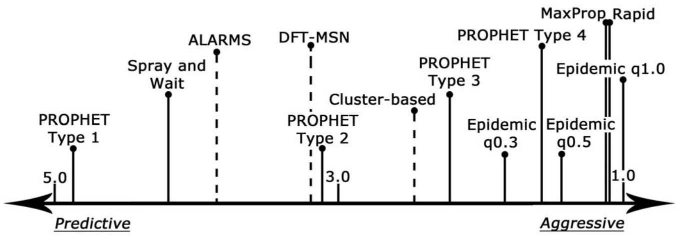


Fig. 2. DTN Routing Protocols on an aggressive to predictive spectrum based on the δ metric

represented by l_e and the total number of duplicate messages by d_e, δ is,

$$\delta = \frac{l_e}{l} \times \frac{d_e}{d}, \tag{1}$$

for a given routing protocol with end-to-end delay l and number of duplicate messages d. This new metric is useful in measuring the effectiveness of the routing protocol in scenarios with relatively low message generation rate. Considering the number of duplicate messages in the network when each message gets delivered, captures the abstract notion of predictive ability; i.e. if a protocol can keep the latency low while also keeping the number of duplicate messages low in comparison with Epidemic routing, its forwarding decisions are more purposeful in moving towards the destination.

C. Extensions to ONE software

We extended the ONE tool to implement the variations of Epidemic and PROPHET presented in section III-A as well as the collection of the proposed metrics. A variation of the random waypoint mobility model was also developed, called random waypoint mobility with quadrants. This mobility model dictates that a node will chose to travel half the time to any point in the simulation area, and half the time to a specific quadrant resulting in simple movement patterns that increases the chances of some nodes to meet more often. We implemented support for such quadrant biased random waypoint mobility to incorporate a correlation between history of encounters and future possibility of encounters. Existence of such a correlation allows us to study the effectiveness of protocols like PROPHET that predict future encounters based on past history.

D. Simulation configuration and parameters

The experiment scenarios used for simulation study was based on the following configuration parameter: a simulation space of 4500m x 3400m; a simulation period of 36 hours; about 100 messages being generated and transmitted between the same two nodes; a message time to live of 300 minutes; and nodes that follow a random waypoint mobility model with movement speeds between 7 m/s and 10 m/s and wait times between 10 and 30 seconds. We chose to run the simulation long enough so that at any given point a very small number of outstanding (undelivered) messages were in the network. We also decided to limit the number of possible source and destinations to one each. These decisions were made in order to isolate the results from the complexity introduced by queues in the intermediate nodes and the protocols were compared with the same set of messages.

TABLE I
RESULTS FOR N=20 + 2

Protocol	Duplicates	Latency (s)	Predictive Ability (δ)
E q=1.0	17.61	2988	1.0
MaxProp	17.61	2988	1.1443
Rapid	17.41	3016	1.1553
E q = 0.5	14.06	4931	1.4919
P Type 4	13.71	3894	1.6268
E q = 0.3	13.49	4931	1.7611
P Type 3	10.25	4920	2.3414
P Type 2	6.60	6951	3.0290
SprayAndWait	4.68	5411	4.2919
P Type 1	3.15	7071	4.9182

IV. SIMULATION ANALYSIS

A. Organization of known DTN routing protocols

We conducted simulation experiments with the source and the destination being static with 20 mobile nodes carrying messages between the two nodes to calculate the predictive ability metric δ. The average value for the number of duplicates, end-to-end latency and the predictive ability are shown in Table I for the different routing protocols that were used in these experiments. The protocols are placed in ascending order based on the value of δ, and the plot in Fig.2 is based on the same metric. We notice that the variations of Epidemic (E) are less predictive while the variation of PROPHET (P) are more predictive. Three other protocols, MaxProp, Rapid and SprayAndWait were also studied. The performance of these protocols now can be compared easily using the new metric and are included in both Fig.2 and Table I.

The protocols represented on the spectrum using dotted lines are our estimation of their position in the spectrum based on the underlying algorithm as the simulation tool we used do not support these routing protocols. Brief justifications for these placements are given below:

- **Cluster-based:** Since cluster based routing protocols use a combination of contact probability and direct transmissions, the cluster-based protocol has been placed toward the middle of the scale.
- **ALARMS:** Due to the use of predetermined paths by ALARMS, ALARMS has been placed in the predictive section of the scale.
- **DFT-MSN:** Since DFT-MSN uses a methodology dependent on node contact probability like PROPHET, it has been placed toward the predictive end of the scale.

TABLE II
RESULTS FOR N=10, RANDOM WAY POINT MOBILITY

Protocol	Duplicates	Latency (s)	Delivery Percentage
Epidemic			
q = 0.5	3.37	2512	100
PROPHET			
Type 2	2.7	2525	100

TABLE III
RESULTS FOR N=40, RANDOM WAY POINT MOBILITY

Protocol	Duplicates	Latency (s)	Delivery Percentage
Epidemic			
q = 0.5	14	944	100
PROPHET			
Type 2	5.3	1446	100

TABLE IV
RESULTS FOR N=10, RANDOM WAY POINT MOBILITY WITH QUADRANTS

Protocol	Duplicates	Latency (s)	Delivery Percentage
Epidemic			
q = 0.5	3.9	1952	100
PROPHET			
Type 2	2.68	2285	100

TABLE V
RESULTS FOR N=40, RANDOM WAY POINT MOBILITY WITH QUADRANTS

Protocol	Duplicates	Latency (s)	Delivery Percentage
Epidemic			
q = 0.5	15.9	994	100
PROPHET			
Type 2	4.4	786	100

B. *Comparison of Epidemic and PROPHET*

In order to get better insight into the behavior of these routing protocols, we chose to conduct further experiments with two protocols chosen from either ends of the spectrum. These experiments were conducted with 10 and 40 nodes moving in the simulation space. The average value for the three metrics specified in section III-B are shown for the four combinations with the number of nodes 10 or 40 and the mobility model random waypoint or random waypoint with quadrants in tables II through V. Each table contains results for Epidemic with a q value of 0.5 and PROPHET type 2 protocols. For all of the scenarios we were able to get a 100% delivery percentage allowing us to compare the other two parameters uniformly. As expected the results show that increase in the number of nodes in the network results in the latency of message delivery decreasing as more nodes leads to more encounters among nodes. The results also demonstrate the PROPHET protocol's ability to use past encounters to predict future encounters through the reduction in the latency when the mobility model favors specific quadrants for each of the nodes. A similar reduction in the latency is not observed for q-Epidemic resulting in PROPHET type 2 performing better than q-Epidemic with q=0.5, when random waypoint mobility with quadrants is used in the 40 node scenario. Even though it is likely that q-Epidemic with q=1.0 will still likely have lower latency, the small number of duplicate messages and the small latency demonstrated by PROPHET encourages the idea of using predictive algorithms when there is any relationship between past and future node mobility. An overall improvement of PROPHET was observed when using the quadrant biased mobility due to encounters of the same nodes being more likely to occur.

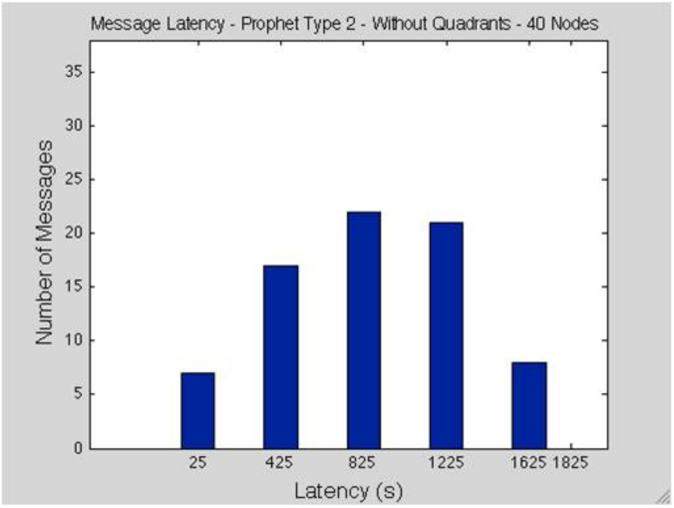
For the 40 node scenarios, we also show the distribution of message latency in Fig.3 and Fig.4 (see next page). Each bar in the graph represents the number of messages that were delivered in the time window between the x-value and the next x-value; for example, the bar at x-value 25 represents the number of messages that were delivered in the window 25 to 425 seconds and the bar at x-value 425 represents the number of messages that were delivered in the window 425 to 825 seconds and so on. As can be seen from Fig.3, the message delay distribution of the PROPHET protocol becomes much more skewed to the left (i.e., lower delay values) when the mobility model is changed from random waypoint mobility to random waypoint mobility with quadrants while Fig.4 shows not much of a change in the distribution for Epidemic protocol when the mobility model is changed.

V. CONCLUSION AND FUTURE WORK

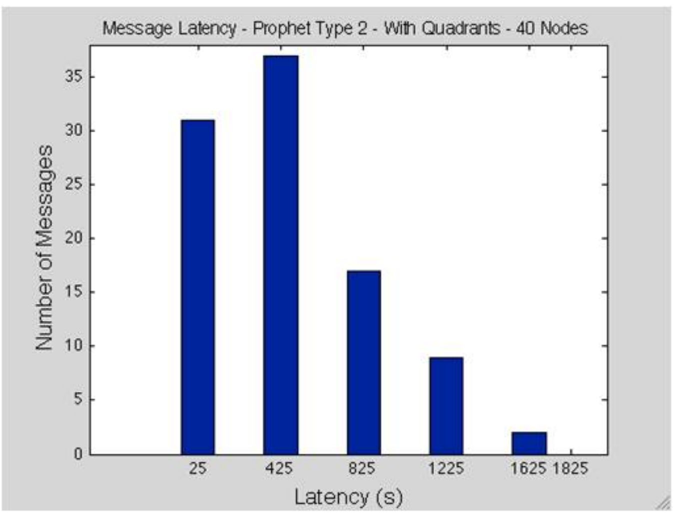
This paper presents the following components of a framework that can be used to conduct simulation analysis of delay tolerant routing protocols:

- A method to organize various known routing protocols in a spectrum ranging from aggressive to predictive based on a newly defined predictive ability metric.
- A collection of variations for the two protocols at the two ends of this spectrum, Epidemic and PROPHET.
- A new mobility model based on random waypoint mobility that increases the propensity for groups of nodes to meet each other more often.
- Extensions to the well know ONE simulation tool to implement these new protocols and mobility models.
- Three interrelated performance metrics that capture different aspects of the performance behavior of these routing protocols and a derived metric that represents their predictive ability.
- Carefully selected simulation configuration parameters that provide an environment to compare DTN routing.
- A subset of results collected from simulation experiments based on this framework.

The framework has allowed us to gain an important insight about the PROPHET protocol: its elaborate predictive scheme does not always translate into significant performance gain; for example, under a random way point mobility model, the

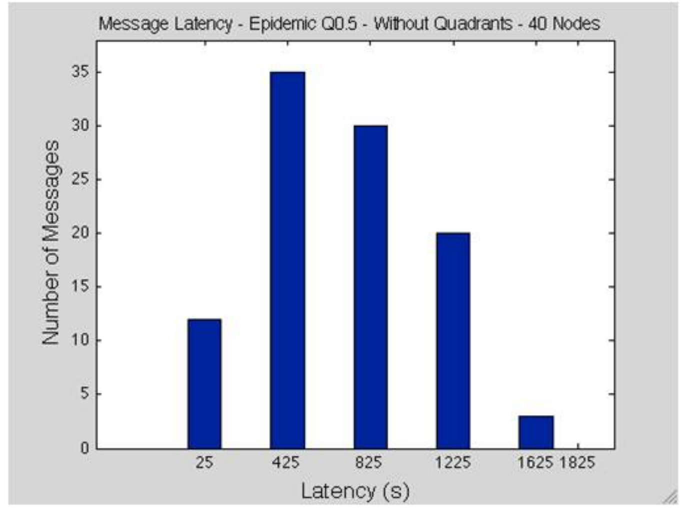


(a) PROPHET: Random Waypoint Mobility

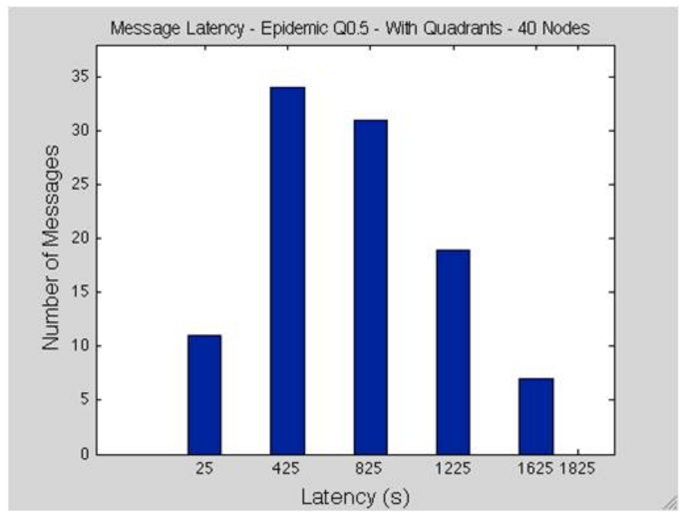


(b) PROPHET: RWM with Quadrant Preference

Fig. 3. PROPHET: Latency Distribution



(a) Epidemic: Random Waypoint Mobility



(b) Epidemic: RWM with Quadrant Preference

Fig. 4. Epidemic: Latency Distribution

much simpler q-Epidemic protocol with a suitable q value can perform equally well with respect to the proposed metrics. We plan to build on this work to extend the framework to include new scenarios that will consider the impact of the finite size queues in the nodes, and message prioritization to further develop insights into DTN routing.

References

[1] Amin Vahdat and David Becker, "Epidemic routing for partially connected ad hoc networks", Tech- nical Report CS-200006, pp. 1-6,Duke University, April 2000.

[2] Hongyi Wu, Yu Wang, Ha Dang, and Feng Lin, "Analytic, Simulation, and Empirical Evaluation of Delay/ Fault-Tolerant Mobile Sensor Networks," in IEEE Transactions on Wireless Communications, Vol. 6, No. 9, pp. 3287-3296, 2007.

[3] A. Lindgren, A. Doria, O. Schelen, "Probabilistic Routing in Intermittently Connected Networks", In Proceedings of the The First International Workshop on Service Assurance with Partial and Intermittent Resources (SAPIR 2004), August 2004, pp. 1-7, Fortaleza, Brazil.

[4] Yi Xian, Chin-Tser Huang, and Jorge Cobb, Look-Ahead Routing and Message Scheduling in Delay-Tolerant Networks, In Proc. of The 35th IEEE Conference on Local Computer Networks (LCN 2010), pp. 40-43, Denver, Colorado, October 2010.

[5] Ha Dang and Hongyi Wu, "Clustering and Cluster-Based Routing Protocol for Delay-Tolerant Mobile Networks", in IEEE Transactions on Wireless Communications, Vol. 9, No. 6, pp. 1874-1881, 2010.

[6] T. Spyropoulos, K. Psounis, C. Raghavendra, Spray and Wait: An Efficient Routing Scheme for Intermittently Connected Mobile Networks, Proceedings of ACM SIGCOMM05 Workshops, pp. 1-6, August 2005.

[7] Aruna Balasubramanian, Brian Neil Levine, and Arun Venkataramani, "DTN Routing as a Resource Allocation Problem", In Proc. ACM SIGCOMM, pp. 1-4, 2007.

[8] J. Burgess, B. Gallagher, D. Jensen, and B. N. Levine, "MaxProp: Routing for Vehicle-Based Disruption- Tolerant Networks", In Proc. IEEE Infocom, pp. 1-3, April 2006.

[9] Ari Keränen and Jörg Ott and Teemu Kärkkäinen,"The ONE Simulator for DTN Protocol Evaluation", in SIMUTools '09: Proceedings of the 2nd International Conference on Simulation Tools and Techniques, Rome, Italy, pp. 1-8, 2009.