Efficient Adaptive Routing in Delay Tolerant Networks

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***Abstract*—Conventional routing algorithms in mobile ad hoc networks (MANETs), i.e., multi-hop forwarding, assume the existence of contemporaneous source-destination paths and are not scalable to large networks. On the other hand, in delay tolerant networks (DTNs), routing protocols use the mobility-assisted, store-carry-forward paradigm which allows delivery among disconnected network components. Adaptive routing, which combines multi-hop and mobility-assisted routing protocols, is of practical value: it allows efficient multi-hop forwarding while providing the flexibility to deliver messages among disconnected network components. However, existing adaptive routing protocols use mobility-assisted routing protocols as an alternative only when the former fails. In this paper, we propose to improve the performance of adaptive routing from a resource allocation point of view, in situations where bandwidth is critical and limited resources affect routing performance. We propose an adaptive routing protocol named efficient adaptive routing (EAR), which allocates bandwidth (or forwarding opportunities) between its multi-hop forwarding component and its mobility-assisted routing component dynamically to improve routing performance. Simulations are conducted to evaluate the routing performance of EAR under different network parameters.**

Keywords: Adaptive routing, delay tolerant networks (DTNs), mobile ad hoc networks (MANETs), simulation.

I. Introduction

In conventional mobile ad hoc networks (MANETs), routing algorithms [1], [2] assume that contemporaneous source-destination paths always exist and messages are delivered in a single-copy, multi-hop manner. On the other extreme, delay tolerant network (DTN) routing algorithms [3], [4], [5], [6], [7], [8], assume that the network is very sparse and highly mobile, and messages are delivered in a multi-copy, mobility-assisted manner.

Existing multi-hop routing protocols in MANETs and mobility-assisted routing protocols in DTNs can be combined to increase the adaptivity in unforeseen network scenarios. In this paper, we focus on adaptive routing, which is able to use multi-hop forwarding (with proactive route maintenance or reactive route discovery) and mobility-assisted forwarding. The challenge lies in coordinating these two routing components efficiently to improve routing performance in terms of delivery rate.

Previous works have used adaptive routing to fill the gap between multi-hop routing and mobility-assisted routing algorithms. Mirco et al. [9] propose to use DSDV [2] for routing in the same connected network component and then focus on a mathematical framework to calculate the utility of each mobility-assisted forwarding when the destination is not in the same component. Ott et al. [10] propose an integrated multi-hop and mobility-assisted protocol, in which a modified AODV [1] is proposed whose broadcast routing requests search for the destination and the available DTN-enabled nodes at the same time. When AODV fails, mobility-assisted routing is used as the alternative.

The commonality of existing adaptive routing algorithms is that the multi-hop routing component is always prioritized and mobility-assisted routing is used as an alternative to extend the connectivity of the network. Such routing protocols could be less efficient than mobility-assisted routing protocols, for example, in networks with high nodal mobility or high traffic rates. This paper focuses on the coordination of the two forwarding protocols in adaptive routing and investigates bandwidth allocation between them, which has not been studied before. We propose *efficient adaptive routing* (EAR), which contains a simple multi-hop routing component and a simple mobility-assisted routing component. The objective of EAR is to improve bandwidth utility by dynamically allocating bandwidth to these two routing components according to real-time statistics in DTNs when network parameters, such as network density and nodal mobility patterns, are unknown.

The contributions of this paper are summarized as follows.

1) We show the possibility of improving the routing performance of the adaptive routing protocol from resource allocation.
2) We propose a heuristics to allocate bandwidth between the two components in our proposed protocol EAR.
3) We perform simulation studies to evaluate the adaptive performance of EAR under a wide range of network parameters.

This paper is organized as follows. Section II presents the basic idea of EAR. Section III describes our method on bandwidth allocation. Section IV shows our simulation methods and results. Finally, Section V concludes the paper with directions for future research.

II. Efficient Adaptive Routing (EAR)

Our proposed EAR routing protocol allocates bandwidth between the two routing components by limiting the maximum bandwidth consumed by multi-hop forwarding. We define a logical cloud for each node, and we limit bandwidth consumed

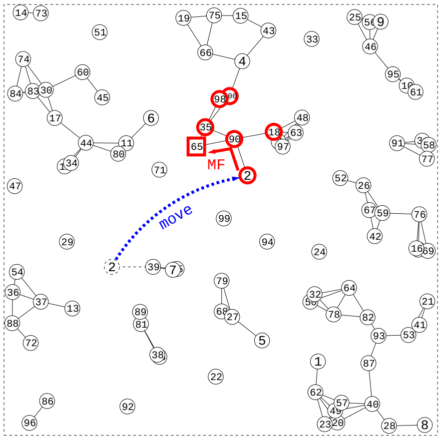


Fig. 1. A message is received by node 65 from node 2 (whose logical cloud includes node 65) through a multi-hop forwarding (MF).

by the multi-hop forwarding by requiring that a node can only forward messages to the other nodes in its logical cloud using multi-hop forwarding.

Definition 1 (Logical cloud): The logical cloud C of a node u is a set of nodes such that, for any $v \in C$, there exists a path from u to v consisting of node in C. The logical cloud must contain the u and all 1-hop neighbors of u.

According to Definition 1, a logical cloud C of a node u is a subset of the connected network component containing u. Given the minimum size $|C|_{min}$ of a logical cloud, we determine the member of the logical cloud as follows: (1) adds all u and all of the 1-hop neighbors of u to C; (2) while $|C| < |C|_{min}$, add to C one of the k-hop ($k > 1$) neighbors v which has the highest priority $(H(u,v), ID(v))$ among the nodes not in C.

$H(u,v)$ is defined as the reciprocal of the hop-count between u and v, and $ID(v)$ is simply the identity (or any hash function of the identity) of v. That is, a smaller hop-count is the first priority and ties are broken by comparing IDs. As an example, in Figure 1, the logical cloud of node 65 with $C = 6$ consists of nodes 18, 35, 65, 90, 98, 100, and 97. After node 2 became a 1-hop neighbor of node 90, the local cloud was updated by replacing node 97 with node 2.

Given a logical cloud size, the bandwidth consumed by the multi-hop forwarding protocol of a node is limited and independent of the network size. The logical cloud size is also used to limit the bandwidth consumption in the proactive/reactive maintenance of the shortest paths.

Our focus is on efficient bandwidth allocation. For simplicity, we use DSDV [2] as the multi-hop routing component, and spray-and-wait [11] as the mobility-assisted routing component. In future work, they can be replaced by other protocols, such as AODV [1] and spray-and-focus [12].

A. The DSDV multi-hop routing component

Destination-Sequenced Distance-Vector Routing (DSDV) [2] is a table-driven routing scheme for ad hoc mobile networks based on the Bellman-Ford algorithm. In DSDV, each node maintains a hop-count of the shortest path to every other node. The DSDV routing component differs from the original DSDV in that it only maintains the hop-count of the shortest path to the nodes in its logical cloud.

Let K be the average size of the logical clouds of the nodes in the network. The amortized bandwidth consumption of the proactive route maintenance is $O(K)$, since in our DSDV routing component, each node needs to periodically broadcast its routing table to its neighbors. This routing table contains items for the nodes in its logical cloud.

B. Spray-and-wait mobility-assisted routing component

The mobility-assisted routing component used in EAR is spray-and-wait [11]. In the original spray-and-wait, each new message is (1) forwarded to a fixed number, L, of nodes, and (2) these L copies are carried by the nodes until the first of the nodes encounters the destination.

A variation of the original spray-and-wait is used in EAR. This variation differs in the fact that there is no maximum number L, which means spray-and-wait can use the rest of the bandwidth to maximize the delivery rate. Specifically, each message is associated with a logical ticket whose value is initially set to 1.0. Whenever a message is copied to another node, the values of the tickets on the sender and the receiver equal half of the original value of the ticket of the sender. To ensure that all messages have equal chances of being sprayed to the other nodes, a node first sprays the messages with larger ticket values.

III. A Heuristic for Efficient Bandwidth Allocation

It is important to find an appropriate bandwidth allocation to improve the overall routing performance of the adaptive routing protocols. We present a heuristic for efficient bandwidth allocation by maximizing bandwidth utility, assuming that the network is homogeneous (in which each node forwards messages for the other nodes) and the mobility of the nodes is randomized (such as in a random waypoint mobility model).

Our method for allocating bandwidth is to determine the logical size C for all the nodes. After C is determined, each node selects the nodes in its logical cloud. Whenever a node has a forwarding opportunity, it first forwards the messages whose destinations are in its logical cloud (closer destinations first), and then sprays messages.

We define B to be the available total bandwidth of a node. In other words, B is the volume of all messages that are received or sent per node per unit of time. For adaptive routing, B includes the bandwidth consumed by the data messages, the metadata of mobility-assisted routing (which is 0 in spray-and-wait), and the proactive route maintenance messages for the multi-hop forwarding protocol. Let R be the average volume of the data messages delivered per destination per unit of time. Obviously, $R \le B$.

Definition 2 (Bandwidth utility): The bandwidth utility U of a routing protocol is the ratio of the volume of the data messages delivered to the volume of total messages consumed in the network. Specifically, $U = R/B$.

The objective of the efficient bandwidth allocation is to achieve the highest bandwidth utility U by properly dividing the total bandwidth B into three parts (1) B_S, the bandwidth allocated to spraying copies of the messages in the network, (2) B_F, the bandwidth allocated to the multi-hop forwarding, and (3) B_P, the bandwidth allocated to the proactive route maintenance in the logical cloud of each node. Here, B_F and B_P are implicitly related. We will approximate B_S, B_F, and B_P respectively using the average cloud size C. Then, we use a heuristic to find a C under which the efficient bandwidth allocation is achieved.

A. The bandwidth consumption of spraying

Suppose the size of logical cloud C is 1, i.e., the logical cloud of each node u contains no other node but u itself and none of the nodes know the identity of their neighbors. In such a scenario, a number of copies of each message are sprayed into the network, but no copy can be further forwarded to its destination. The volume of data messages received per node per time unit $R_1 = B_S/N$ (1 denotes that the size of the logical cloud is 1), where B_S is the amount of bandwidth consumed by spraying copies of the messages and N is the number of nodes in the network. $R_1 = B_S/N$ because the probability of the destination of the message being u is $\frac{1}{N}$ when a node u receives a message.

B. The bandwidth consumption of forwarding

We assume that the messages received by each node in the spraying scheme are independent, i.e., two nodes will not have more common messages because they are geometrically closer to each other. This assumption is acceptable when the mobility of the nodes is high enough. If the logical cloud size is $C > 1$, then the volume of messages received per node per time unit $R_C = R_1 C$. This is because for each node u the rate at which it receives messages whose destination is u is R_1, and so is the rate of any other nodes receiving messages with destination u. Assume that each node u is also in the logical cloud of C other nodes and that those C nodes will forward those messages to u whenever they get them; the receiving rate of u is increased by C times. Therefore, $R_C = R_1 C = \frac{B_S C}{N}$.

Forwarding messages inside logical clouds consumes a per node bandwidth B_F. Let K be the average hop-count between a node and another node in its logical cloud, $B_F = R_C K$. This is because, in a homogeneous network, a node having a receiving rate R_C suggests that it has the same receiving rate R_C of messages that are destined to any of the other nodes in its logical cloud. Therefore, the bandwidth B_F consumed by forwarding these messages to their destinations in the same cloud is $R_C K$. We approximate K by $C/2$ considering that, in sparse networks, the connected components are likely to have a linear topology (as can be observed in Figure 1). Then, we have,

$$B_F = R_C = K R_C \frac{C}{2} = \frac{B_S C}{N}\frac{C}{2} = \frac{B_S C^2}{2N}.$$

C. The bandwidth consumption of proactive route maintenance

If the average size of the logical cloud is C, the average bandwidth consumed in the maintenance of the shortest paths of a node in its logical cloud is $O(C)$. This is because each node needs to periodically broadcast its routing table containing items for each node in its logical cloud, whose size is C. The bandwidth B_P consumed by the proactive maintenance can be represented by $B_P = MC$, where M is a constant that depends on the frequency of the periodical broadcast and the size of data item for each node in the logical cloud.

D. Maximum bandwidth utility

We use Theorem 1 to approximate the maximum bandwidth utility.

Theorem 1: The maximum bandwidth utility is approximately achieved when the average logical cloud size C is $\sqrt{2N}$, where N is the network size.

Proof: The average bandwidth utility can be approximated by,

$$U = \frac{R_C}{B} = \frac{R_C}{B_S + B_F + B_P} = \frac{\frac{B_S C}{N}}{B_S + \frac{B_S C^2}{2N} + MC}.$$

Assuming B_S is independent of C, since the bandwidth $B_F + B_P$ allocated to the multi-hop forwarding is determined only by variable C, we can change the value of C to achieve the maximum bandwidth utility. The value of C with which the maximum bandwidth utility is achieved can be calculated by setting $\frac{dU}{dC} = 0$. First,

$$\frac{dU}{dC} = \frac{d(\frac{\frac{B_S C}{N}}{B_S + \frac{B_S C^2}{2N} + MC})}{dC}$$

$$= \frac{(B_S + \frac{B_S C^2}{2N} + MC)d(\frac{B_S C}{N}) - \frac{B_S C}{N} d(B_S + \frac{B_S C^2}{2N} + MC)}{(B_S + \frac{B_S C^2}{2N} + MC)^2}$$

$$= \frac{(B_S + \frac{B_S C^2}{2N} + MC)\frac{B_S}{N} - \frac{B_S C}{N}(\frac{B_S C}{N} + M)}{(B_S + \frac{B_S C^2}{2N} + MC)^2}.$$

When $\frac{dU}{dC} = 0$, we have,

$$(B_S + \frac{B_S C^2}{2N} + MC)\frac{B_S}{N} - \frac{B_S C}{N}(\frac{B_S C}{N} + M) = 0$$

$$\Rightarrow (B_S + \frac{B_S C^2}{2N} + MC) - C(\frac{B_S C}{N} + M) = 0$$

$$\Rightarrow B_S + \frac{B_S C^2}{2N} + MC - \frac{B_S C^2}{N} - MC = 0$$

$$\Rightarrow B_S - \frac{B_S C^2}{2N} = 0 \Rightarrow C = \sqrt{2N}.$$

■

Theorem 1 shows that the maximum bandwidth utility can be achieved approximately by selecting an average cloud size

TABLE I
SIMULATION PARAMETERS

Parameters	Default	Range
Field size	$1,000 \times 1,000(m^2)$	
Number of nodes	200	50-250
Message rate	1 (msgs/s)	1-10(msgs/s)
Buffer size	1,000	100-1,000
Data message size	2KB	
Radio bandwidth	1Mb	
Transmission range	100(m)	
Message TTL	1,000(s)	100-1,000(s)
Simulation time	2,000(s)	
Moving speed in RWP	100(m/s)	
Pause time in RWP	50(s)	20-200(s)

$C = \sqrt{2N}$ when the number of nodes in the network is N. If the network size N is unknown, C can be approximated from B_S and R_C, which can be collected statistically by the nodes based on message transmission history. Since,

$$R_C = \frac{B_S C}{N} \Rightarrow N = \frac{B_S C}{R_C},$$

we have,

$$C^2 = 2N = 2\frac{B_S C}{R_C} \Rightarrow C = \frac{2B_S}{R_C}.$$

An algorithm to maximize bandwidth utility is described as follows: (1) $C = 1$ initially, (2) C is updated periodically according to the current statistics of B_S and R_C: C is increased by 1 if $C < \frac{2B_S}{R_C}$, and (3) C is decreased by 1 if $C > \frac{2B_S}{R_C}$.

IV. Simulation & Results

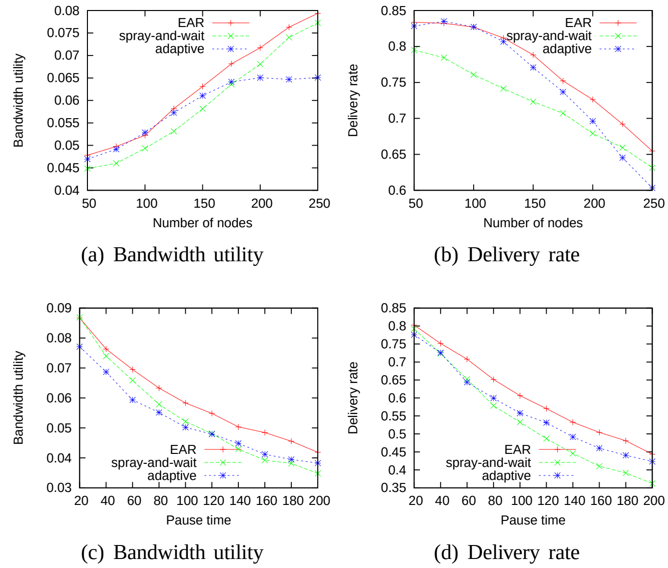
A. Implementation & settings

We implemented our simulation on the JiST/SWANS simulator [13]. Our implementation of a DTN node includes (1) a neighbor discovery mechanism using periodical beacons, (2) a reliable broadcast operation using delayed acknowledgments, (3) a message vector exchange mechanism which prevents redundant message forwarding, (4) a buffer management mechanism, (5) DSDV, and (6) spray-and-wait.

To draw a comparison, we also implemented two other protocols which can be regarded as variations of EAR: the spray-and-wait protocol [11] whose logical cloud is limited to 1-hop neighbors, and an adaptive DTN routing protocol which has no limitation on the size of its logical cloud, which is simply denoted as *adaptive*. Our metrics are bandwidth utility and delivery rate. Simulation parameters are network size, nodal mobility step, message time-to-live (TTL), and message buffer size. The main simulation parameters are summarized in Table I.

B. Simulation results and discussions

In the first set of simulations (Figures 2(a) and 2(b)), we vary the number of nodes from 50 to 250. As shown in Figure 2(a), the bandwidth utility of EAR and spray-and-wait increases almost linearly as the number of nodes increases. This is because as density increases, each broadcast can send



(a) Bandwidth utility (b) Delivery rate (c) Bandwidth utility (d) Delivery rate

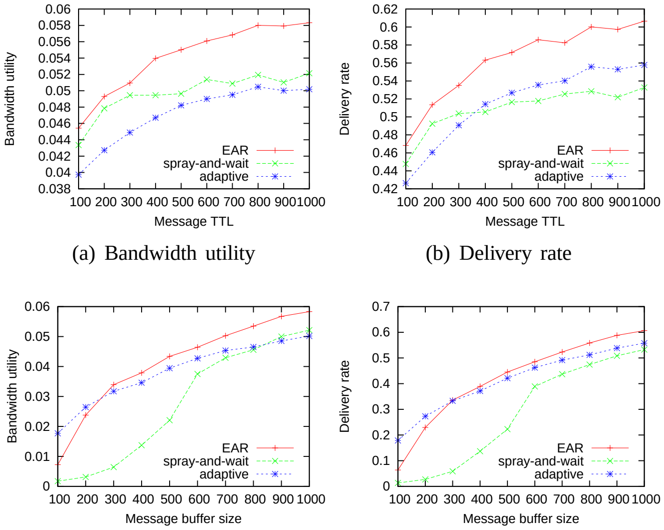
Fig. 2. Performance comparison with different message pause time and number of nodes.

a message to more nodes. The bandwidth utility of spray-and-wait is, on average, 10% smaller than EAR and is the best under different numbers of nodes, which shows that our protocol does in fact adaptively improve the bandwidth utility. The bandwidth utility of adaptive stops increasing as the number of nodes is more than 200. This is because the size of the connected component increases as the number of node increases. The bandwidth used by multi-hop forwarding increases and eventually consumes all the bandwidth.

Figure 2(b) shows that the delivery rate of all routing algorithms decreases as the number of nodes increases. The delivery ratio of EAR is 5-15% better than that of spray-and-wait. That of adaptive shows the worst degradation among all of the protocols as the number of nodes increases, and its performance becomes the worst when the number of nodes is over 200. Looking at Figure 2(a), we can see that the delivery rates are closely related to the bandwidth utility – the protocols that have better bandwidth utility also have better delivery ratios. This can be explained by their definitions.

In the second set of simulations (Figures 2(c) and 2(d)), we increase the pause time of the nodes in the random waypoint mobility model from 20 to 200. As shown in Figure 2(c), the bandwidth utility of all protocols decreases as pause time increases. This is because the spray-and-wait component relies on the mobility of the network. Moreover, when mobility is extremely low, a message is not guaranteed to be delivered within its TTL, even with infinite bandwidth. The bandwidth utility of EAR is 10-30% higher than that of adaptive and is also higher than that of spray-and-wait by up to 20%.

Figure 2(d) shows that the delivery rate of all of the protocols decreases as pause time increases, and the trends are much the same as the bandwidth utility shown in Figure 2(c). EAR has the highest delivery rate and when the pause time



(a) Bandwidth utility (b) Delivery rate

(c) Bandwidth utility (d) Delivery rate

Fig. 3. Performance comparison with different TTLs and message buffer sizes.

is 200 seconds, the delivery rate of EAR is 50% higher than that of spray-and-wait.

In the third set of simulations (Figures 3(a) and 3(b)), we vary the message TTL from 100 to $1,000$ seconds. As shown in Figure 3(a), the bandwidth utilities of all protocols increase as the TTL of the messages increases. The bandwidth utility of EAR is the best under different message TTLs. The bandwidth utility of spray-and-wait does not increase as significantly as the other two protocols. When message TTL is larger than 500 seconds, the bandwidth utility of EAR is at least 15% higher than those of spray-and-wait and adaptive.

Figure 3(b) shows that the delivery rates of all the protocols increase as message TTL increases, and EAR has the highest delivery rate under different message TTLs. When message TTL is greater than 500 seconds, the improvement in delivery rate when using EAR as opposed to spray-and-wait and adaptive are 10% and 15% respectively.

In the last set of simulations (Figures 3(c) and 3(d)), we vary the message buffer size from 100 to $1,000$ messages per node. As shown in Figure 3(c), as the message buffer size increases, the bandwidth utility increases for all protocols. This is because as the buffer size decreases, some of the messages have to be removed before they expire. From the figure, adaptive has the best performance with a very small buffer. The bandwidth utility of spray-and-wait is the most sensitive to buffer size, and it degrades most significantly when the buffer size is smaller than 600 messages. Comparatively, EAR is more tolerant to a small buffer size: its bandwidth utility is worse than adaptive's only when the buffer size is smaller than 300 messages.

Figure 3(d) shows that the delivery rate of the protocols change in much the same way as bandwidth utility when the message buffer size changes. Figure 3(d) shows that EAR and adaptive are much better than spray-and-wait as the message buffer is small.

C. Summary of simulation

The simulation results show that EAR outperforms the other protocols in terms of delivery rate since it has a better bandwidth utility. Thus, it can be concluded that delivery rate is closely related to the bandwidth utility. From the simulation results, we found that the performance of EAR does not decrease when the performance of one of the other two deteriorates and the other does not. This shows that EAR combines the advantages of the protocols, and it can improve the routing performance with its ability to allocate more bandwidth to the better routing component under different network settings.

V. Conclusions

In this paper, we proposed to improve the performance of adaptive routing from a resource allocation point of view. Simulation results show our proposed routing protocol, EAR, has better routing performance than the compared protocols.

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References

[1] S. R. Das, C. E. Perkins, and E. M. Royer. Performance comparison of two on-demand routing protocols for ad hoc networks. In *Proc. of IEEE INFOCOM*, 2002.

[2] C. Perkins and P. Bhagwat. Highly dynamic destination-sequenced distance-vector routing (DSDV) for mobile computers. In *Proc. of Conference on Communications Architectures, Protocols and Applications in conjection with SIGCOMM 94*, 1994.

[3] J. Ghosh, S. J. Philip, and C. Qiao. Sociological orbit aware location approximation and routing (SOLAR) in MANET. In *Proc. of ACM MobiHoc*, 2005.

[4] J. Haas, J. Y. Halpern, and Li Li. Gossip-based ad hoc routing. In *Proc. of IEEE INFOCOM*, 2002.

[5] J. Leguay, T. Friedman, and V. Conan. DTN routing in a mobility pattern space. In *Proc. of ACM SIGCOMM Workshop on Delay-Tolerant Networking*, 2005.

[6] C. Liu and J. Wu. Routing in a cyclic mobispace. In *Proc. of ACM MobiHoc*, 2008.

[7] S. Merugu, M. Ammar, and E. Zegura. Routing in space and time in network with predictable mobility. In *Technical Report: GIT-CC-04-07, College of Computing, Georgia Tech*, 2004.

[8] A. Vahdate and D. Becker. Epidemic routing for partially-connected ad hoc networks. In *Technical Report, Duke University*, 2002.

[9] M. Mirco, H. Stephen, and M. Cecilia. Adaptive Routing for Intermittently Connected Mobile Ad Hoc Networks. In *Proc. of IEEE WoWMoM*, June 2005.

[10] J. Ott, D. Kutscher, and C. Dwertmann. Integrating DTN and MANET routing. In *Proc. of ACM SIGCOMM Workshop on Challenged Networks (CHANTS)*, 2006.

[11] T. Spyropoulos, K. Psounis, and C. Raghavendra. Efficient routing in intermittently connected mobile networks: The multi-copy case. In *ACM/IEEE Journal of Transactions on Networking*, 2007.

[12] Thrasyvoulos Spyropoulos, Konstantinos Psounis, and Cauligi Raghavendra. Spray and focus: Efficient mobility-assisted routing for heterogeneous and correlated mobility. In *Proc. of the International Workshop on Intermittently Connected Mobile Ad hoc Networks (ICMAN), in conjunction with IEEE PerCom*, 2007.

[13] http://jist.ece.cornell.edu/.