Performance Study of Routing Schemes in Delay Tolerant Networks

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Abstract

In conventional networks, such as the Internet, it is assumed that there exists a fully connected path between any pair of nodes at any time. In Delay Tolerant Networks (DTN), however, the connected path may be broken, and nodes may be partitioned into two disconnected subsets because of the movement or failure of some nodes. Thus, the data transmission requirements can not be satisfied by traditional routing schemes. How to efficiently route data in DTNs has therefore become a critical and challenging issue. To address the problem, we propose a contact-duration-based probabilistic routing scheme (PR_CD) based on the probabilistic routing scheme PRoPHET[16] (PR). Each node in the PR_CD scheme predicts the current network condition by using contact information, and then chooses appropriate relay nodes to improve the delivery rate as well as reduce the transmission latency and transmission overhead. To evaluate the efficacy of the proposed scheme, we use simulations to conduct a comprehensive study of different DTN routing mechanisms. We believe such a study is important because the ability to characterize the behavior and performance of routing schemes plays a key role in the understanding and design of DTNs.

Keyword: Data Routing, Probabilistic Routing, Delay Tolerant Network, Opportunistic Network.

1. Introduction

The traditional Internet is connected by wired networks that embody several positive characteristics, such as continuous end-to-end paths, short delays, and low error rates. However, wireless devices are becoming increasingly popular because of the rapid advances in communication technologies. In theory, such devices allow users to connect to the Internet anywhere, any time, but it is not always possible for a user to find an access point. To address the problem, we propose a novel approach that uses relay nodes to deliver data to users. Because the range of wireless transmissions is limited, nodes might be separated into different clusters. We consider the characteristics of DTN nodes in order to find an efficient way to deliver data.

The movements of nodes affect their connections. In a DTN, two nodes are said to be in *contact* if they are within communication range and they can share their data. The contact period of a pair of nodes is called the *inter-contact time,* and the length of the contact period is called the *contact duration.*

DTNs also have three important limitations. First, the intermittent nature of the links means that end-to-end paths do not exist. Second, because paths fail sometimes, the transmission latency may be extremely long. Third, the links between nodes may be disconnected, which leads to a high error rate on routes. Traditional Internet routing protocols can not provide acceptable solutions for DTN networks. Because of these limitations, finding an appropriate routing protocol is an important issue in DTN design.

Several kinds of routing mechanisms have been proposed. Basically, the mechanisms match the types of contact mentioned above. The first called *scheduled routing* is based on the nodes' previous contact times and information about the duration of those contacts. It follows a fixed mobility pattern and decides which data should be transmitted to a particular relay node [1][2]. The second type, called *predicted routing*, uses a priori information to predict contact between nodes in order to deliver data [3][4][9][10]. Although there is no fixed mobility pattern in the random contact situation, it is still possible to find a model to deliver data to its destination successfully. The third type of mechanism is called *opportunistic routing*. Under this mechanism, a node sends all the data to any encountered nodes that do not have that data. It does not consider whether the receiving nodes are capable of delivering the data successfully [5][6][7][8].

In this paper, we propose a contact-duration-based probabilistic routing scheme called PR_CD. Under the scheme, each node predicts the current network condition based on contact information, and then chooses appropriate relay nodes to improve the delivery rate as well as reduce the transmission latency and transmission overhead. To evaluate the efficacy of the proposed scheme, we use simulations to conduct a comprehensive study of different DTN routing mechanisms. We believe such a study is important because the ability to characterize the behavior and performance of routing schemes plays a key role in the understanding and design of DTNs.

The remainder of the paper is structured as follows. In Section 2, we introduce various routing mechanisms. In Section 3, we discuss the advantages of PRoPHET (Probabilistic Routing Protocol using a History of Encounters and Transitivity) and propose our PR_CD scheme. Section 4 reports the simulation results and compares our approach with traditional routing mechanisms. Then, in Section 5, we provide some concluding remarks and indicate the direction of future research.

2. Related work

An intuitive way to design a DTN routing mechanism is to allow a pair of nodes to transmit their data to the destination directly while they are in contact. This kind of mechanism is known as direct transmission. Another way to transmit data is via a moving relay node, called a two-hop relay node [11]. Although these two mechanisms improve the delivery rate by increasing a node's mobility, a two-hop relay can only send N copies to N nodes. If the relay node and the sender cannot make any contact with the destination, the data can not be delivered. How to decide the value of N is therefore an important issue. Depending on the characteristics of the transmission, three kinds of routing scheme can be used, namely replication-based routing, knowledge-based routing, and code-based routing. We discuss these schemes in the following sub-sections.

2.1. Replication based

Data replication schemes send a packet that is a copy of the original data. The delivery rate can be improved by increasing the number of copies of the packet. Epidemic routing is a typical example of such a scheme [5]. When two nodes, A and B, make contact, A informs B about the data it is holding. If B does not have the data, it asks A to forward it. Since this is very similar to flooding, we call it a *controlled flooding mechanism*.

Harras et al. [6] try to improve routing by transmitting willingness and a packet's TTL to control the number of copies. They introduced the concept of a cure, which heals the sender or other nodes by sending a cure-ack packet.

2.2. Knowledge based

Knowledge-based routing schemes include scheduled and predicted routing mechanisms. Scheduled routing mechanisms [1] need information about the previous contact time and contact duration as well as the storage capacity of the network to calculate the best route path linearly. Predicted routing mechanisms [2] need information about the link error rate to predict routing paths and the number of data copies to achieve the best delivery rate. In real networks, it is not easy to obtain correct information about the link error rate; however, based on the history of contacts, we can predict the mobility of nodes. This information helps us decide which nodes should become relay nodes and how to reduce network traffic. We can also use the nodes' mobility patterns [4] to help choose relay nodes.

2.3. Coding based

Using different kinds of coding techniques to encrypt data is called coding-based routing. Widmer et al. [8] proposed a combination of network coding (NC) [12][13] and the Epidemic routing protocol. Each data packet is uniquely encoded by using network coding. A node only needs to receive enough packets to decrypt the data, which.improves the delivery rate.

Estimation-based Erasure Coding (EBEC) [9] combines erasure coding and a replication scheme. Adjust how many erasure-coding blocks by average contact times. The hybrid erasure coding (HEC) proposed in [10] combines erasure coding and aggressive forwarding. Under aggressive forwarding, all packets are sent sequentially during in the nodes' contact period. If a node's battery is dead or the node loses mobility, it can not deliver data to the destination. This is known as the 'black hole' information loss problem. The HEC model uses the nodes' contact duration efficiently and applies erasure coding to solve the black hole problem caused by aggressive forwarding.

3. PRoPHET Enhancement

3.1. Overview of PRoPHET

The basic concept of PRoPHET (PR) is the same as that of the Epidemic scheme in that two nodes exchange packets when they make contact. The PR scheme can also calculate the predictability of successful data delivery based on the contact history. The scheme only transmits data to an encountered node if that node can improve the data delivery rate. We define the predictability of successful data delivery from node A to node B as follows:

$$P_{(a,b)} = P_{(a,b)old} + (1 - P_{(a,b)old}) \times P_{init} \quad (1)$$

where P_{init} is a non-zero initialization constant value between 0 and 1, and $P_{(a,b)old}$ is the value of $P_{(a,b)}$ before the update step. The more frequent the contact between nodes, the higher the predictability of successful delivery will be. The transitivity principal is used to calculate the delivery predictability of a relay node (Eq. 2):

$$P_{(a,c)} = P_{(a,c)old} + (1 - P_{(a,c)old}) \times P_{(a,b)} \times P_{(b,c)} \times \omega \quad (2)$$

ω is a non-zero value between 0 and 1 that represents the prediction weight increased by the transitivity. By iteratively calculation, the credibility of transitivity drops because losing relay node's information. Therefore, we need to update the predictability by the aging constant γ, which is a non-zero constant. The number of time units that have elapsed since the last aging time k is calculated as follows:

$$P_{(a,b)} = P_{(a,b)old} \times \gamma^k \quad (3)$$

3.2. Delivery Predictability

The PR protocol considers a nodes' contact history to calcultat the predictability. In the other way, the last contact happened earlier, the possibility of next contact is lower. However, for human mobility patterns, this assumption is not always correct. Hence, based on this assumption, we propose a modification that considers the contact duration. When two nodes have the same predictability; we choose the one with the longer contact duration to improve the transmission rate.

We propose the following two formulas to improve the PR by additional information.

3.2.1. Contact utilization. We assume the network has N nodes in the past T seconds, the contact time of nodes A and B is denoted by $T_{A,B}$. The predictability of one hop delivery is:

$$P^1_{A,B} = \frac{T_{A,B}}{T} \tag{4}$$

In two-hop delivery (one relay node), the predictability of nodes A and B is

$$P^2_{A,B} = \sum_{\substack{1 \le i \le N \\ i \ne A, i \ne B}} (P^1_{A,i} \times P^1_{i,B}) \tag{5}$$

The predictability of nodes A and B is the summation of the predictabilities of A to B by one relay node.

To calculate the predictability of successful transmission from A to B in m-hops this forms in general:

$$P^m_{A,B} = \sum_{\substack{1 \le i \le N \\ r_i \ne A,\ r_i \ne B \\ r_i \ne r_j;\ \forall 1 \le i, j \le m\ 1}} (P^1_{A,r_1} \times P^1_{r_1,r_2} \times \bullet\ \times P^1_{r_{m\ 1},B}) \tag{6}$$

Thus, the predictability of nodes A and B is

$$P_{A,B} = \sum_{i=1}^{m} \omega^{i\ 1} P^i_{A,B} \tag{7}$$

Except for one-hop delivery, the predictability is the summation of other hop count's predictability multiplied by a weight factor, which adjust the importance of the multi-hop effect.

The calculation in (4) has three advantages over PR. First, the delivery predictability is not be affected by contact time of two nodes during T seconds. In a fixed inter-contact time model, there is no need to consider the last contact time because one-hop delivery predictability only considers the contact during T seconds. Second, considering the contact time can solve two nodes had contacted for long time ago but still exists in the contact history. That causes predictability extreme low in the PR. It is not correct in human mobility pattern. However, using information about the contact duration will improve that. Third, multi-hop delivery predictability avoids the loop problem in PR, as shown in Figure 1.

We propose a new mechanism, which is explained in the following steps. 1) There is no contact between nodes A and B, but A had contacted C previously; thus, we can calculate $P_{a,c}$. 2) Node A makes contact with B, so node B can send data to C via A. Node B updates $P_{a,b}$ and $P_{b,c}$. 3) Node A and B make contact again. Because node B has $P_{b,c}$, node A will update $P_{a,c}$. Actually, $P_{,b.c}$ was delivered from node A, so we should not update the predictability with this information about nodes A and C. Our modification can eliminate the loop problem based on the node's history. We call this the PR_CU routing scheme.

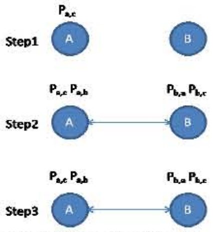


Figure 1: Contact history of node A and B

3.2.2. Contact duration ratio. A relay node can contact multiple nodes in a network, as shown in the following equation:

$$P^1_{A,B} = \frac{T_{A,B}}{\sum_{i=1}^{N} T_{A,i}} \tag{8}$$

Node A compares the portions of contact time with node B to the total contact time with node i.

We call this the PR_CD routing scheme.

4. Evaluation

4.1. Simulation scenarios

In this section, we evaluate the performance of the modified PR scheme and some DTN routing mechanisms, namely, Epidemic, NC and HEC. To evaluate our platform, we use the DTMSIM [14] simulator, which is based on the Java application. We built a network scenario with ZebraNet [15], which is an observation of Zebra's activity for two days in the real world. We can simulate any days with the model. Figure 2 shows the nodes' contact characteristics. More then 70% of the node pairs contact less or equal than 3 times. The contact duration of these nodes is greater than that for the remaining 30%. To create more complex scenarios, we reduce the contact duration of the remaining 30%. The original ZebraNet scenario is called ZebraNet1. The complex scenario, called ZebraNet2, is shown in Table 1. The experiment configuration is shown in Table 2.

A larger number of node pairs means a heavier traffic load. We use different traffic loading scenarios to determine the effectiveness of the compared routing mechanisms. Each node pair is selected randomly and generated every 1,000 seconds. The nodes' storage capacity is 400 Mbytes. Each result is the average of 10 experiments.

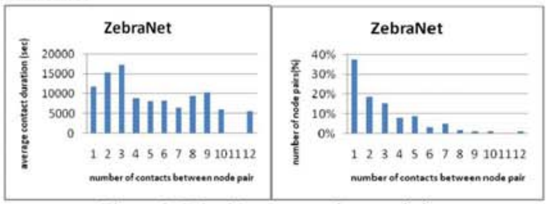


Figure 2. ZebraNet contact characteristics

Table 1. Contact characteristics

	ZebraNet1	ZebraNet2
Avg contact duration/pair/day(sec)	22,211	12,825
Avg # of contacts/pair/day	2.06	2.06
Number of nodes	34	34

Table 2. Configuration of the experiment

Trace Name	ZebraNet1, ZebraNet2
CBR Traffic (1 MB/msg)	1 msg/hour
Contact bandwidth	1 MB/sec
H (hop count limit)	5
m(computation depth)	4
T (time interval)	2 days
Number of pairs	1, 10, 20, 30
Buffer size	400 MB
Simulation time	16 day
ω	0.25
P_{init}	0.75
γ	0.98
••	20 secs

4.2. Evaluation 1: Modifications to PRoPHET

Figure 3 shows the data delivery rate with different numbers of node pairs in ZebraNet1. We observe that PR_CU and PR_CD have higher delivery rates than the original PR scheme. The modifications improve the transmission rate, but the contact duration does not differ much for different numbers of node pairs. This explains why the delivery rates are similar in each result, as shown in Figure 4.

In Figure 4, $C_{A,B}$ denotes the contact between nodes A and B. Based on the contact history, the delivery predictability from node A to C is higher than that from node B to C in PR_CU, but the delivery predictability from node B to C is higher in PR_CD. If node B needs to send data to nodes C and D, it will deliver all the data to node A under PR_CU. Because of limited storage, this might cause buffer overflow on the relay node. Under PR_CD, node B only sends data for node D to node A, which eliminates the possibility of overflow. In the other words, the probability of a hot spot is higher under PR_CU. Meanwhile, PR_CD performs better in terms of load balance because it has higher predictability for a node that is not a hot spot. This reduces the risk of the node becoming a hot spot and storage overflow. The delivery rate improves if overflow can be avoided. The larger the number of node pairs, the more data there is in the network. The overflow problem will affect PR_CU easily. In this situation, PR_CD achieves a better performance. On the other hand, PR_CU performs better in low traffic situations.

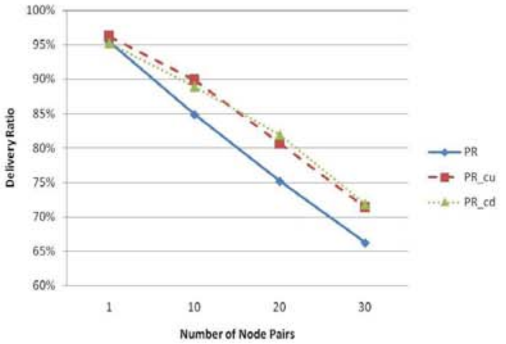


Figure 3. Delivery ratio in ZebraNet1

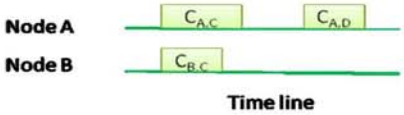


Figure 4. Contact history of nodes A,B

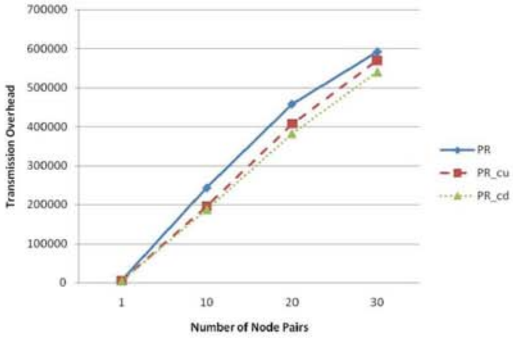
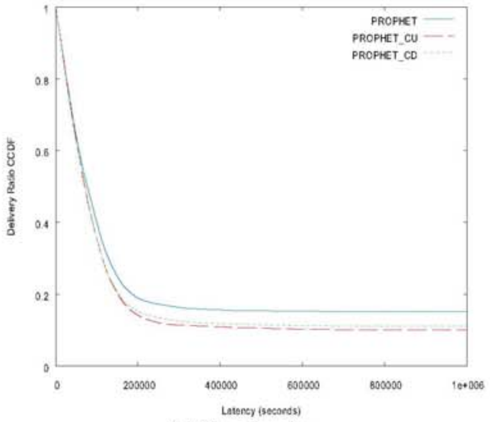


Figure 5. Transmission overhead in ZebraNet1

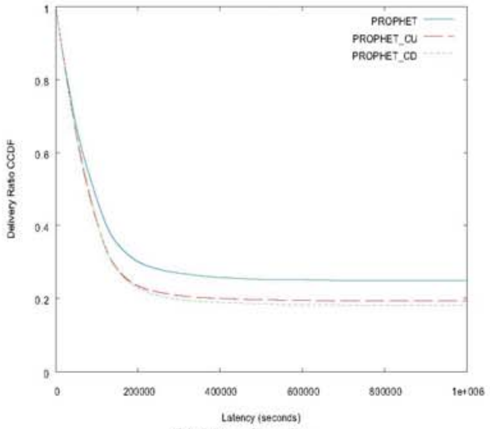
Figure 5 shows the transmission overhead of ZebraNet1 with different numbers of node pairs. The PR_CU and PR_CD schemes achieve better data delivery rates and have lower transmission overheads. The transmission overhead of PR_CD is a little lower than that of PR_CU because it experiences fewer overflow problems. Nodes do not have to transmit the same data repeatedly.

Figure 6 shows the latency for different numbers of node pairs. For the same data delivery rate, the latencies of our modified versions are shorter than in the original version. The modifications not only improve the data delivery rate, but also reduce the transmission latency.

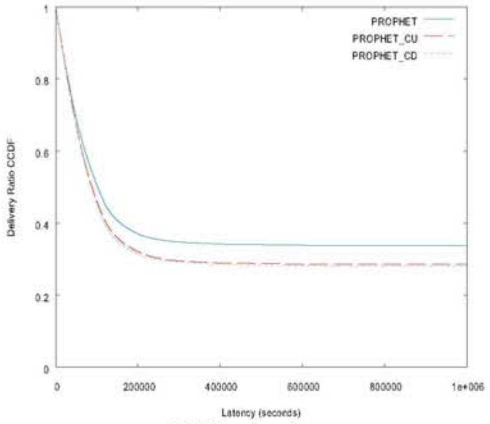
With 10 pairs of nodes, there are only a few data packets in the network. This explains why the performance of PR_CU improves when the data delivery rate is higher then 80%.



(a) 10 node pairs



(b) 20 node pairs



(c) 30 node pairs

Figure 6. Average transmission delay in ZebraNet1

Figure 7 shows the data delivery rate for different node pairs. By reducing the contact duration by 30%, all the delivery rates in ZebraNet2 are lower than in ZebraNet1, because the contact duration is shorter. The modifications to PR achieve a better data delivery rate than the original protocol. The performances of PR_CU and PR_CD also depend on the storage size and data delivery rate. In a limited storage environment, PR_CD performs better. The transmission overhead and latency of ZebraNet2 are as same as in ZebraNet1.

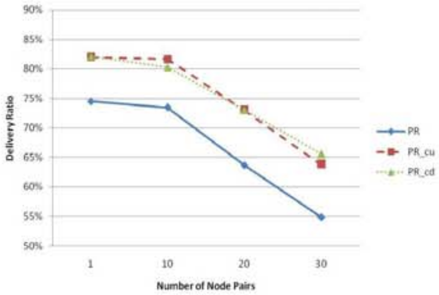


Figure 7. Delivery ratio in ZebraNet2

4.3. Evaluation 2: Analysis of routing mechanism

We now compare different kinds of routing mechanisms for DTN. We modify the method in [8] from many-to-many to single-to-single, and allow multi-node pairs. We call this mechanism the Network Coding (NC) scheme. Figure 8 shows the data delivery rates for different node pairs in ZebraNet1. For a node pair, NC's delivery rate is lower than that of PR_CD because the number of packets is limited by the forwarding factor. In a lightly-loaded network, the delivery rates of PR_CD, Epidemic, and NC are almost the same. HEC does not employ the same strategies as the other schemes. For example, it does not deliver data to the first node it encounters if it is the destination node. Moreover, it does not erase copies when a data packet is delivered successfully, send packets in a queue sequentially, or only send packets that an encountered node does not have. Therefore, we do not consider HEC in the rest of the analysis.

Figure 9 shows the transmission overhead for different node pairs in ZebraNet1. By increasing the number of node pairs, the Epidemic transmission overhead increases rapidly, while NC's overhead increases more slowly than that of PR_CD.

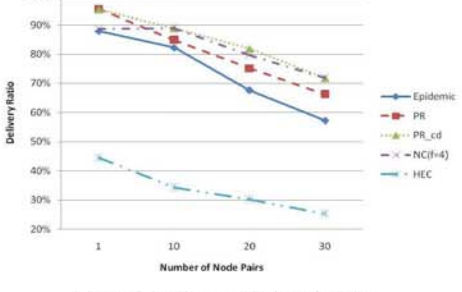


Figure 8. Delivery ratio in ZebraNet1

Figure 10 shows the delivery ratio and the error rate when there are 30 node pairs. Because the relay node does not have the ability to check errors, NC's performance will suffer when errors occur. The error also spreads to the next node, so the data delivery rate will decline. Thus, we suggest that network coding should not be used in a network with a high error rate. In contrast to NC, Epidemic and PR only send one copy of a data packet. Hence, if there is an error, they still have a chance to deliver the correct data to the destination.

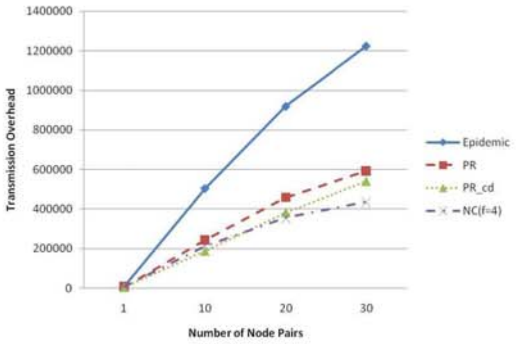


Figure 9. Transmission overhead in ZebraNet1

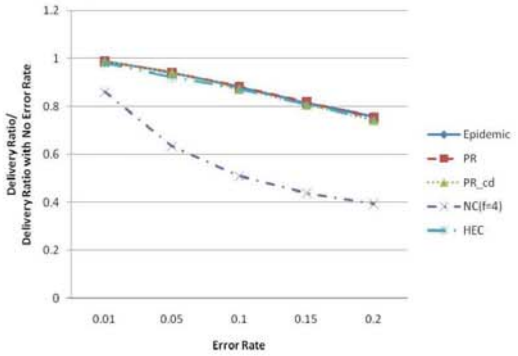


Figure 10. Delivery ratio with error rate in ZebraNet1

5. Conclusion

In Delay Tolerant Networks (DTN), the nodes are wireless devices and mobile. Consequently, a connected path may be broken, and nodes may be partitioned into two disconnected subsets because of the nodes' movements. Thus, the data transmission requirements can not be satisfied by traditional routing schemes. We have proposed two improvements to the PR protocol that consider contact utilization and contact duration to adapt the protocol to different scenarios. We have shown that the modifications achieve a better data delivery rate, shorter transmission latency and lower transmission overhead than the original PR scheme.

We also compared several routing mechanisms in order to understand their characteristics. Epidemic only performs well in low traffic networks. In congested situations, NC achieves the best data delivery rate, but it does not work well when errors occur in a network. Although HEC has the lowest data delivery rate, it can survive in high error environments. In the future, we hope to design a new mechanism with NC and PR to improve the data delivery rates.

6. References

[1] J. Alonso, K. Fall. A linear programming formulation of flows over time with piecewise constant capacity and transit times. Intel Research Technical Report IRB-TR-03-007, June 2003.

[2] S. Jain, K. Fall, and R. Patra. Routing in a delay tolerant networks. In *Proceedings of ACM SIGCOMM,* vol. 34, pp. 145-158, ACM Press, October 2004.

[3] S. Jain, M. Demmer, R. Patra, and K. Fall. Using redundancy to cope with failures in a delay tolerant network. In *Proceedings of ACM SIGCOMM,* pp. 109-120, October 2005.

[4] J. Leguay, T. Friedman, and V. Conan. Evaluating mobility pattern space routing for DTNs. In *IEEE Infocom*, April 2006.

[5] A. Vahdat and D. Becker. Epidemic routing for partially-connected ad hoc networks. Technical Report CS-2000-06, Duke University, July 2000.

[6] K. A. Harras, K. C. Almeroth, and E. M. Belding-Royer. Delay tolerant mobile networks (dtmns): Controlled flooding in sparse mobile networks. In *IFIP Networking*, April 2005.

[7] Y. Wang, S. Jain, M. Martonosi, and K. Fall. Erasure coding based routing for Opportunistic Networks. In *ACM SIGCOMM Workshop on Delay Tolerant Networks (WDTN'05)*, August 2005.

[8] J. Widmer and J.-Y. L. Boudec. Network coding for efficient communication in extreme networks. In *ACM SIGCOMM Workshop on Delay Tolerant Networks (WDTN'05)*, August 2005.

[9] Y. Liao, K. Tan, Z. Zhang, and L. Gao. Estimation based erasure-coding routing in delay tolerant networks. In *International Wireless Communications and Mobile Computing Conference*, 2006.

[10] L.-J. Chen, C.-H. Yu, T. Sun, Y.-C. Chen, and H. hua Chu. A hybrid routing approach for Opportunistic Networks. In *ACM SIGCOMM Workshop on Challenged Networks*, 2006.

[11] M. Grossgluser and K. N. C. Tse. Mobility increases the capacity of ad hoc wireless networks. In *IEEE/ACM Transactions on Networking*, vol. 10, pp. 477-486, August 2002.

[12] P. A. Chou, Y. Wu, and K. Jain. Practical network coding. In *Proc. Allerton*, October 2003.

[13] S.-Y. R. Li. R. W. Yeung, and N. Cai. Linear network coding. In *IEEE Transactions on Information Theory*, February 2003.

[14] Delay tolerant network simulator http://www.dtnrg.org/code/dtnsim.tgz

[15] The ZebraNet wildlife tracker. http://www.princeton.edu/ mrm/zebranet.html

[16] A. Lindgren, A. Doria, and O. Schelen. Probabilistic routing in intermittently connected networks. In *ACM SIGMOBILE Mobile Computing and Communications Review*, vol. 7, number. 3, pp. 19–20, July 2003.