

HYMAD: Hybrid DTN-MANET Routing for Dense and Highly Dynamic Wireless Networks

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Abstract

In this paper we propose HYMAD, a Hybrid DTN-MANET routing protocol which uses DTN between disjoint groups of nodes while using MANET routing within these groups. HYMAD is fully decentralized and only makes use of topological information exchanges between the nodes. We evaluate the scheme in simulation by replaying real life traces which exhibit this highly dynamic connectivity. The results show that HYMAD outperforms the multi-copy Spray-and-Wait DTN routing protocol it extends, both in terms of delivery ratio and delay, for any number of message copies. Our conclusion is that such a Hybrid DTN-MANET approach offers a promising venue for the delivery of elastic data in mobile ad-hoc networks as it retains the resilience of a pure DTN protocol while significantly improving performance.

1 Introduction

When transporting data through a wireless mobile ad-hoc network, the Delay/Disruption-Tolerant Network (DTN) [7] paradigm uses node mobility as an advantage while compromising on message delivery delays [8]. Message forwarding decisions are made on a *per-encounter* basis, for example by using utility functions based on aggregating statistics on node meeting probabilities [10, 4, 9]. At any given time, a node's vision of the network topology is limited to its current neighbor. It does not have complete or even local knowledge of the actual network topology as in the conventional Mobile Ad-hoc Network (MANET) routing schemes. While this makes perfect sense in extremely sparse networks [3, 1], there are situations where a highly mobile network is dense and sufficiently well connected to provide end-to-end connectivity between a significant subset of its nodes.

These nodes may even form small islands of stability. Using MANET principles within such islands can bring great improvements. Indeed, it considerably increases each node's information of its local topology, thus leading to better forwarding decisions. When high mobility rates and more generally high link instabilities reduce route life-times and threaten network-wide end-to-end connectivity, a MANET routing protocol can still succeed locally even if it fails globally.

In this paper we propose HYMAD, a Hybrid DTN-MANET routing protocol. HYMAD combines techniques from both traditional ad-hoc routing and DTN approaches. HYMAD periodically scans for network topology changes and builds temporary disjoint groups of connected nodes. Intra-group delivery is performed by a conventional ad-hoc routing protocol and inter-group delivery by a DTN protocol.

HYMAD constantly adapts to the dynamics of the wireless ad-hoc network using only topological information. As in traditional ad-hoc routing, no extra information on geographical location or social community membership is required. It does not rely on a priori knowledge of connectivity patterns or inter-meeting times. This makes HYMAD amenable to implementation in a DTN stack or ad-hoc routing protocol [11]. In a dense network, HYMAD can function similarly to a traditional MANET protocol. In the other extreme case of very sparse connectivity, each node is a group on its own and HYMAD behaves like a classical DTN routing protocol. In any other intermediate case its hybrid nature takes over.

We implemented the HYMAD hybrid approach with a self-stabilizing group service [5, 6] and the multi-copy Spray-and-Wait protocol as the DTN routing scheme [13]. We evaluated the scheme by performing simulation runs on the Rollernet data set [14], an example of a highly dynamic ad-hoc network, and show that it brings substantial performance improvements over pure Spray-and-Wait.

In the next section, we further describe how our

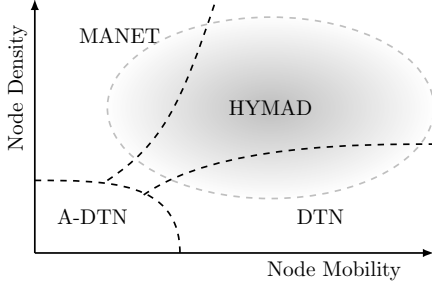


Figure 1: Mobility vs Density: when different paradigms apply

hybrid approach positions itself compared to existing DTN and MANET approaches. In section 3, we describe the HYMAD routing protocol principles. We explain how nodes can agree on forming disjoint groups and how such groups rather than individual nodes can be used as the basis for DTN routing. We then evaluate the scheme on a real data set, the Rollernet experiment, in section 4. Finally we conclude our work in section 5.

2 Routing in a mobile wireless network

Mobile wireless ad-hoc networks were first studied under the assumptions of moderate node mobility and sufficient density to ensure end-to-end connectivity. Both conditions are necessary for traditional MANET approaches, be they proactive or reactive.

Let us characterize the various occurrences of mobile wireless networks along the two main parameters of **node density and node mobility**. In Fig. 1, which maps the different routing approaches on the bi-dimensional mobile wireless network space, traditional MANET routing appears in the top left corner.

When the density of nodes diminishes end-to-end connectivity can disappear. **In such sparse networks nodes have very few, if any, neighbors within their transmission ranges. The topology eventually splits into several non-communicating connected components.** This is typically the realm of **Delay Tolerant Networking** which one can further subdivide in two [2]: the Assisted DTNs (A-DTN), in case of low mobility of nodes, or Unassisted DTNs (U-DTN) where mobility is high. The latter corresponds to traditional DTN scenarios.

Routing in A-DTNs typically involves special mobile nodes, known as message ferries or data mules, which relay the messages between the separate connected components [16, 12]. **The packet-switching method of MANETs is replaced with a store-and-forward ap-**

proach.

When the mobility in sparse networks increases, mobile nodes begin to meet others. This is the traditional DTN scenario, where nodes forward one or more copies of a given message until it reaches its destination. There are many strategies for optimizing the forwarding decision. **The most straightforward approaches, such as Epidemic or Spray-and-Wait [13] do not require nodes to acquire information on the others' positions, movements or trajectories. More elaborate schemes involve a utility function where each node collects direct and indirect knowledge of other nodes' meeting probabilities. They require a certain learning period to aggregate statistics before making good forwarding decisions. For example, Lindgren et al. [10] use past encounters to predict the probability of meeting a node again while Daly et al. [4] use local estimates of betweenness and similarity.**

In dense networks, conventional MANET protocols start to break down under high mobility down even if the network is almost always fully connected. **Indeed the sheer instability of the links would result in a deluge of topology updates in the proactive case and route error and new route requests messages in the reactive case.** DTNs protocols on the other hand can handle high mobility regardless of the density of the network. However by narrowly focusing on per-encounter events, they ignore a lot of available information. For example, simply asking nodes to regularly broadcast a list of their neighbors would give all nodes a picture of its two-hop neighborhood even under high mobility. Repeat this once and everyone knows their three hop neighborhood. A node may therefore have a topology "knowledge horizon" which determines how far into the real topology a node can "see". The more extreme the mobility, the shorter the "horizon".

The Hybrid DTN-MANET approach that we advocate in this paper aims at filling the gap for efficient routing in highly connected and highly mobile networks, which have so far, to the best of our knowledge, received little attention. Hybrid DTN-MANET routing, like the HYMAD protocol that we describe below, **combines the resilience of DTNs with the greater knowledge of local network topology provided by a MANET protocol.** It adapts naturally to the dynamics of the network and its applicability spans a large spectrum of the mobile wireless network space.

3 The HYMAD protocol

3.1 Overview

The core idea in HYMAD is to use whole groups of nodes instead of individual nodes as the focus of a DTN protocol. The analogy is detailed as follows:

DTN	HYMAD
Node	Group of nodes
A node has message m	One node in the group has message m and all other nodes in the group know that.
Two nodes meet	Two disjoint groups become connected.

Each node u regularly broadcasts a list detailing for each group member v including itself the following elements:

1. The minimal number of hops from u to v .
2. A list of the messages held by v .
3. A bit indicating if v is a *border node* (i.e. in contact with other groups).

The first two elements are necessary for the inter-group routing protocol. The second one in particular allows a group to agree on what messages it carries and which node (hereafter call the message's custodian) specifically holds it. The last one enables use of an intra-group distance vector routing. As in traditional distance vector algorithms, the number of iterative broadcasts necessary for all members of a group to agree on this information is equal to the diameter of the group.

HYMAD then uses a DTN protocol to transfer messages between groups. The approach is generic and many existing DTN protocols could be employed. In this paper, we use Spray-and-wait [13] to forward messages between disjoint groups. As in Spray-and-Wait, the source of a message will create a certain number of copies of it. In HYMAD however, this source node is part of a group and copies of the message will be distributed among the adjacent groups instead of simply the nodes that the source encounters. If a group has more than one copy, it will, in turn, distribute extra copies to its other adjacent groups. If a group has just one copy it will wait until encountering the destination's group to transfer it. Once inside the destination's group, the intra-group routing protocol delivers the message to the destination.

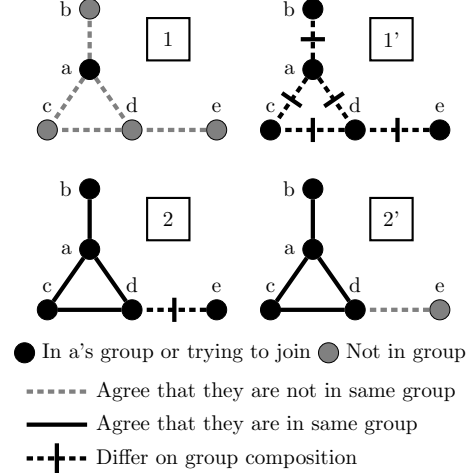


Figure 2: Self-stabilizing groups: convergence in two iterations

3.2 Intra-group routing

In HYMAD, the intra-group routing is handled by a simple distance vector algorithm.

The nodes are dynamically grouped with a distributed network partitioning algorithm. In our implementation, we chose to consider *diameter-constrained groups*. Groups will accept new members as long as its diameter is less than a maximum diameter parameter (D_{max}). If a group's diameter expands due to internal link failure, then some members are excluded to satisfy the diameter constraint. Ducourthial et al. [6] propose a self-stabilizing, asynchronous distributed algorithm that achieves this using an *r-operator* on a slightly modified distance vector. This algorithm converges in $O(D_{max})$ iterations. The proof of self-stabilization using asynchronous message passing can be found in [5].

The main ideas behind group creation and modification are illustrated in Fig. 2 for a maximum diameter $D_{max} = 2$. In the first iteration, node a begins by broadcasting the distance vector ($a : 0$). Nodes b, c and d decide they want to join the group and broadcast ($b : 0, a : 1$), ($c : 0, a : 1$) and ($d : 0, a : 1$) respectively. After receiving the broadcast from d , node e also decides that it wants to join the group and broadcasts ($e : 0, d : 1, a : 2$) (or ($e : 0, d : 1, c : 1, a : 2$) if c spoke before d). In the second iteration, a now broadcasts ($a : 0, b : 1, c : 1, d : 1$), d realizes that the distance between b and e is greater than D_{max} and therefore chooses to exclude e from the group and broadcasts ($d : 0, a : 1, c : 1, b : 2$). Finally e understands that it is not part of the group. After two iterations, the group has stabilized on a, b, c, d . Now let's suppose that at a later date the link between a and c goes down. Node

c now only receives the broadcasted distance vector $(d : 0, a : 1, b : 2)$ from d . It then understands that it is no longer part of the group. As is obvious from this example, a given topology can result in very different groups depending on the order in which the nodes speak.

In this paper, we used this algorithm in a proactive fashion where each node periodically runs the algorithm and broadcasts its distance vector. Group composition therefore changes in reaction to topology changes rather than routing needs.

3.3 Inter-group routing

Border nodes take care of most of the inter-group DTN routing. Indeed, the periodic broadcast protocol described in 3.2 puts them in the unique position of knowing both the composition of two adjacent groups as well as the messages they hold. *Border nodes* may request the custodian of a message to transfer one of more copies to it.

When a *border node* learns that its group has acquired copies of a message that a neighboring group does not possess, it has the following choices:

- If the message's destination is in the neighboring group, request the message from its custodian and pass it on.
- If its group has more than one copy of the message, request $\min\left(1, \left\lfloor \frac{n_c}{n_b} \right\rfloor\right)$ copies from its custodian and pass them on. (n_c is the number of copies and n_b the current number of border nodes in the group). The idea is to fairly spread a group's copies among its adjacent groups.
- Otherwise do nothing

Conversely, when a *border node* receives copies of a new message from an adjacent group it can either:

- If the destination is in its group, forward the message to it using the inter-group routing protocol.
- Otherwise, randomly select a group member to be the custodian for the copies. This is done to spread the burden over members of a group.

With this in place, when a node wants to send a message, it simply adds it to its own list of messages. Through the intra-routing protocol, in $O(D_{max})$ time, the group's *border nodes* will become aware of the new message and request copies to forward it on to the adjacent groups.

3.4 Discussion

An internal link failure may cause a group to split into several separate sub-groups due to its diameter increasing. In such a situation, each sub-group only has a fraction of the messages of the original group. Fortunately this is not really a problem. Firstly, the intra-group protocol detailed in 3.2 ensures that nodes will update their message lists accordingly when removing nodes from their group member lists, thereby preventing a sub-group from advertising messages it does not have or any other such incoherences. Secondly, certain subgroups may still be connected to each other. If either sub-group has more than one copy of some messages, these will be copied over the other sub-group. In any case HYMAD recovers gracefully from group splits.

Choosing a diameter parameter for the group self-stabilization algorithm involves a trade-off. On the one hand, increasing it will expand each node's individual "knowledge horizon" of the actual network topology. Fewer copies will cover a larger portion of the network, which will naturally lead to faster delivery. On the other hand, this comes at the cost of increasing the convergence time and overhead of the group service. Ideally, the convergence speed should be considerably faster than the speed of topology changes. In a sense, extreme mobility may fundamentally limit a node's possible knowledge of the network's topology. The increased overhead results from each node regularly broadcasting a list of all messages in its group. Larger groups mechanically lead to longer control messages. If one is willing to incur the extra cost, the diameter can be set to encompass the entire network. In such a situation, HYMAD resembles a resilient MANET routing protocol using store-and-forward for message transfers. Furthermore, in many mobile wireless scenarios, there are underlying social dynamics at work which can sometimes drive nodes to gather into loose communities. D_{max} should be chosen so as to allow the expected number of members per social group to neatly fit into one self-stabilizing group.

4 Results on Rollernet data

4.1 Methodology

We evaluate HYMAD's performance on Rollernet [14], a highly connected and extremely mobile connectivity trace. The Rollernet experiment involved equipping 62 participants of the regular Sunday afternoon rollerblading tour through Paris with contact loggers (Intel iMotes). In order to witness different behav-

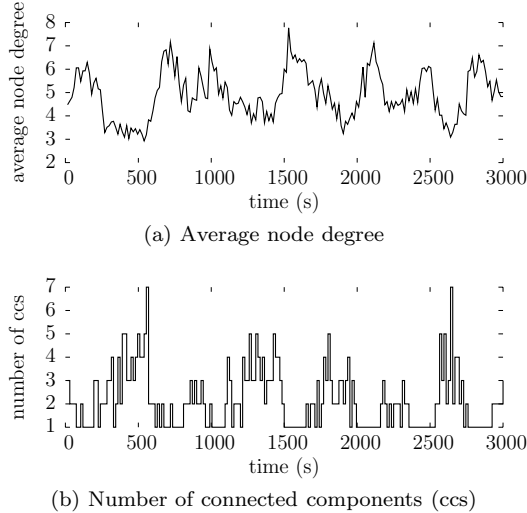


Figure 3: The accordion effect in Rollernet

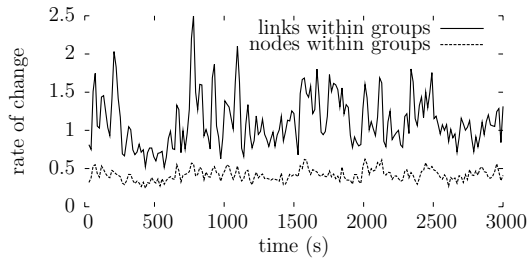


Figure 4: Topology changes: average number of links within a given group that appear or fail vs. number of nodes that leave or join that group

ior profiles the 62 bluetooth loggers were distributed among groups of friends, members of rollerblading associations and staff operators. In particular, one member of the staff was instructed to remain behind the tour times while another stayed in front for the entire duration of the experiment. This allows us to get a rough sense of the relative geographic position of the participants by looking at the connectivity graph. A snapshot of the connectivity graph can be seen in Fig. 6 and an animation is available online [15].

The Rollernet trace is ideal for evaluating HYMAD. Indeed it exhibits the following characteristics:

- *High density:* Contrary to many DTN traces, Rollernet is *not* sparse. A look at Fig. 3a, shows that the average node degree of the connectivity graph oscillates between 2.9 and 7.8. The average for the whole tour is 4.8.
- *High mobility:* Everyone eventually meets everyone else. On average, each of the 62 nodes meets 56 others during the course of the tour. Addition-

ally the topology evolves extremely quickly. The average lifetime of a given link is 26 seconds. The average lifetime of a shortest path between two nodes is 15.5 seconds. Considering that the sampling period is 15 seconds, it follows that links are highly unstable and valid routes transient.

- *Accordion Effect:* This is an interesting consequence of the rollerblading context. The tour alternates between acceleration and deceleration phases in which the network topology respectively expands, leading to several separate connected component, and contracts, leading to a single connected component. Fig. 3b shows that the number of connected components varies between 1 and 7 (17 if counting isolated nodes). In fact, Figures 3a and 3b have roughly alternating phases.

We compare HYMAD to both Epidemic and regular Spray-and-Wait. Epidemic provides an upper bound on achievable performance in terms of both delay and delivery ratio while Spray-and-Wait provides a DTN state-of-the-art comparison. We slightly adapted Spray-and-Wait to the more connected context of Rollernet. A node no longer splits half of its copies with the other nodes it meets, but instead splits its copies equally among itself and its neighbors.

We chose to use $D_{max} = 2$ for all our results because it ensures a very fast convergence rate, keeps the overhead reasonable and seemed to accurately reflect the size of separate connected components (small groups of friends for example), particularly during the accelerating phases. We also tested greater values of D_{max} , which yield, at the cost of greater overhead, a small but noticeable improvement of the delivery ratio.

The sampling period of the Rollernet traces is 15 seconds. We did not try to extrapolate the events (link failures, new contact opportunities, etc..) in the time between multiples of 15 seconds. We also assume that 15 seconds is enough for a message to traverse any connected component in Rollernet. Therefore, all our results on delays when simulating protocols on top over the Rollernet traces will be in multiples of 15 seconds.

4.2 Performance

Extremely high link instability could mean one of two things. Either nodes only briefly stay in the vicinity of one another or that nodes may remain geographically close but that the link fails for other reasons such as briefly moving out of transmission range or excessive contention. We measured between each time step and from each node's point of view, how many of its group members changed (number of new members +

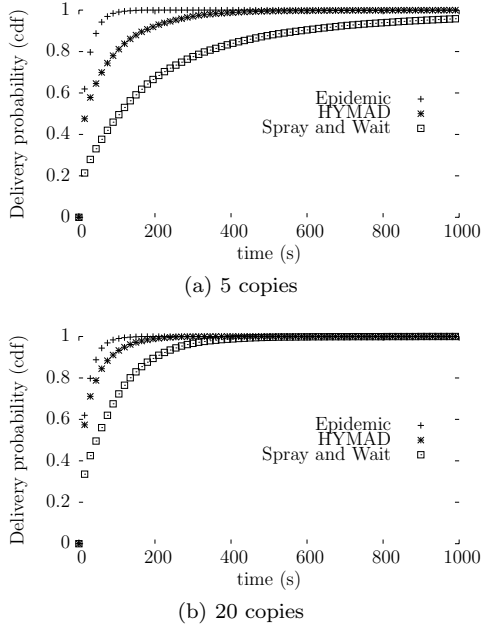


Figure 5: Comparison of delivery probabilities

number of excluded members) and how many links between members of its group changed (either by appearing or disappearing). The averages for all the nodes are shown in Fig. 4. The composition of a given group appears much more stable than the links among its members. This supports the idea that small communities like groups of friends tend to stick together during the tour and that link failures do not necessarily mean that two nodes have clearly moved away from each other. Furthermore, the rate of change of group composition, unlike most other metrics, seems to smooth the accordion effect. This suggests that these groups are indeed a good support for our hybrid approach.

To evaluate the performance of HYMAD we replayed the 3000 seconds of the trace. Every 15 seconds, during the first 2000 seconds, we randomly selected 60 pairs of nodes which were instructed to send a message to each other using Epidemic, HYMAD and Spray-and-Wait. This averages results over both the connected and disconnected phases of Rollernet. Figures 5a and 5b were obtained using the aggregate data from 10 runs of this scenario with respectively 5 and 20 maximum number of copies for HYMAD and Spray-and-Wait. They compare the cumulative distribution function of the delivery probability for the three protocols. A few observations can be made:

- HYMAD clearly outperforms Spray-and-Wait in terms of delay and quickly achieves comparable performance with Epidemic.

- With a low number of copies, HYMAD also outperforms Spray-and-Wait in terms of delivery ratio for reasons explained hereafter.
- Predictably, performance increases with the number of copies. The maximum number of groups (including singletons) obtained at a given time is 29. Therefore, HYMAD with 20 copies will spray practically the entire network and therefore quickly and reliably reach the destination if in the same connected component as the source.

Spray-and-Wait’s simple forwarding scheme performs very well *under the assumption of independent and identically distributed node mobility* [13]. However this is absolutely *not* the case in Rollernet where groups of friends tend to stick together. It is also usually *not* the case in many real-world situations where underlying social dynamics are often at work.

This can have a impact on performance. For example, when using just 5 copies, Spray-and-Wait simply fails to deliver about 5% of messages even after waiting for more than 15 minutes. Using 10 copies, the average delay with Spray-and-Wait (133 seconds) is nearly three times that of HYMAD (48 seconds). To further illustrate this point, Fig 6 compares the propagation of 10 copies after 15 seconds for HYMAD (Fig. 6a) and Spray-and-wait (Fig. 6b). The rightmost node is the head of the rollerblading tour. The bold lines represent intra-group links while the dashed gray lines represent inter-group links. The nodes holding at least one copy are represented by a diamond. In HYMAD’s case, the destination is a diamond meaning that our hybrid approach has delivered its message within 15 seconds. On the other hand, the regular Spray-and-Wait protocol distributed copies mainly within its own local group. These nodes remain close to each other thus increase the delay. In this particular case (Fig. 6b) it will take 525 seconds for a node with a copy to meet the destination

5 Conclusion and further work

In this paper we identified a new class of dense and highly mobile networks not well addressed by conventional DTN or MANET approaches. We proposed a new hybrid approach, HYMAD, that uses nodes’ knowledge of their local group topology to improve the performance of a simple DTN protocol. In our case we used diameter-constrained groups along with distance vector for intra-group routing and Spray-and-Wait for inter-group routing. Simulations of our implementation in a dense and highly mobile network show significant performance improvements over regular Spray-

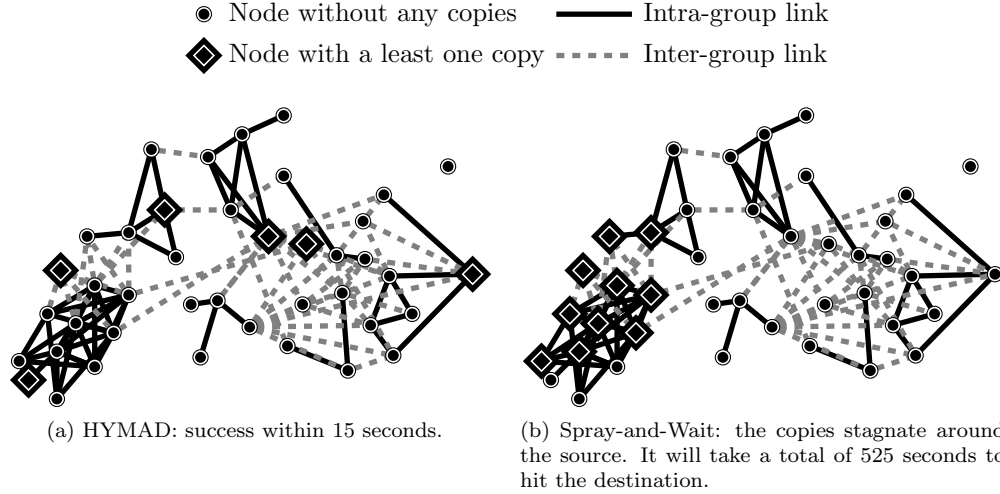


Figure 6: Regular vs Hybrid Spray and Wait routing in Rollernet. (Partial view of the topology at $t=15s$)

and-Wait. Further work includes more comprehensive testing against other real and synthetic mobility scenarios.

HYMAD is an example of a larger class of hybrid DTN-MANET routing protocols which can handle a very wide spectrum of networks that overlaps with those usually handled by either DTN or MANET. We believe that the first results that we obtained are encouraging for further research in this direction. In particular, other more elaborate DTN/MANET protocol pairs could conceivably be used for intra and inter-group routing and would be worth exploring.

Acknowledgments

This work has been partially supported by the RNRT project Airnet under contract 01205

References

- [1] CRAWDAD: A community resource for archiving wirelessdata at dartmouth. <http://crawdad.cs.dartmouth.edu>.
- [2] V. Borrel, M. H. Ammar, and E. W. Zegura. Understanding the wireless and mobile network space: a routing-centered classification. In *Proc. ACM CHANTS*, 2007.
- [3] J. Burgess, B. Gallagher, D. Jensen, and B. N. Levine. MaxProp: Routing for Vehicle-Based Disruption-Tolerant Networks. In *Proc. IEEE Infocom*, 2006.
- [4] E. Daly and M. Haahr. Social network analysis for routing in disconnected delay-tolerant MANETs. In *Proc. ACM MobiHoc*, 2007.
- [5] S. Delaët, B. Ducourthial, and S. Tixeuil. *Self-Stabilizing Systems*, chapter Self-stabilization with r-Operators Revisited, pages 68–80. Springer, 2005.
- [6] B. Ducourthial, S. Khalfallah, and F. Petit. Algorithme de gestion de groupe pour les réseaux ad hoc fortement dynamiques. In *AlgoTel*, May 2008.
- [7] K. Fall. A delay-tolerant network architecture for challenged internets. In *Proc. ACM SIGCOMM*, 2003.
- [8] M. Grossglauser and D. N. C. Tse. Mobility increases the capacity of ad hoc wireless networks. *IEEE/ACM Trans. Netw.*, 10(4):477–486, 2002.
- [9] M. Grossglauser and M. Vetterli. Locating nodes with ease: Last encounter routing in ad hoc networks through mobility diffusion. In *Proc. IEEE Infocom*, 2003.
- [10] A. Lindgren, A. Doria, and O. Schelen. Probabilistic routing in intermittently connected networks. In *Proc. SAPIR*, 2004.
- [11] J. Ott, D. Kutscher, and C. Dwertmann. Integrating dtn and manet routing. In *CHANTS '06: Proceedings of the 2006 SIGCOMM workshop on Challenged networks*, 2006.
- [12] R. C. Shah, S. Roy, S. Jain, and W. Brunette. Data mules: Modeling a three-tier architecture for sparse sensor networks. In *Proc. IPSN*, 2003.
- [13] T. Spyropoulos, K. Psounis, and C. Raghavendra. Spray and wait: an efficient routing scheme for intermittently connected mobile networks. In *Proc. WDTN*, 2005.
- [14] P.-U. Tournoux, J. Leguay, F. Benbadis, V. Conan, M. D. de Amorim, and J. Whitbeck. The accordion phenomenon: Analysis, characterization, and impact on dtn routing. In *Proc. IEEE Infocom*, 2009.
- [15] J. Whitbeck. Animation of rollernet connectivity graph. <http://www.youtube.com/watch?v=kdkCx1x1MkI>.
- [16] W. Zhao and M. H. Ammar. A message ferrying approach for data delivery in sparse mobile ad hoc networks. *ACM Mobihoc*, 2004.