Routing in Large Wireless Multihop Networks with Irregular Topologies

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***Abstract*— Position-based routing protocols forward packets solely based on geographical information about nodes. Therefore, in irregular topologies where routing along a straight line to the destination is not feasible due to voids, they choose suboptimal paths. In this paper, we propose a position-based protocol MRA that tries to capture the global network topology on a large scale from overheard data packets and, if necessary, actively transmits explorer packets to find shorter paths. The required additional memory at the nodes can be kept small by applying a fish-eye like view on the network, where distant areas are aggregated to zones. A node does only forward packets in a certain direction for a given destination zone when it also has previously received packets from this direction and originating in that destination zone. Thus, MRA does not route packets along infeasible paths where packets cannot be forwarded directly to the destination due to voids. Simulation results show that MRA is able to find up to 40% shorter paths than other position-based protocol in irregular network topologies.**

***Index Terms*— ad-hoc networks, routing, swarm intelligence**

I. Introduction

ROUTING in wireless multihop networks has generated a lot of interest and a large number of routing protocols have been proposed. We can distinguish between topology-based protocols such as AODV [1] and OLSR [2] and position-based routing protocols like GFG/GPSR [3], [4] and GOAFR [5]. Position-based routing protocols assume that nodes are aware of their positions e.g. through GPS. Each node forwards packets greedily to one of its neighbors closer to the destination. A recovery mechanism has to be applied if no neighbor is closer and this greedy routing fails. Unlike topology-based protocols, position-based protocols require only little control traffic and do not need to maintain paths. Thus, they are scalable and more robust to changes in the network topology than topology-based protocols, which make them the preferred choice for large and highly dynamic networks. However, position-based routing protocols show also some shortcomings. They typically suffer from drawbacks such as:

- Routing a packet along the line-of-sight between the source and destination may often not be possible in realistic networks due unpopulated areas or mountains and lakes. Thus, greedy routing of position-based protocols will fail and the recovery mechanism must be applied. The path chosen may be very suboptimal as shown in an example in Fig. 1, where packets are forwarded greedily towards node C first instead towards node A when routing from S to D.
- Each packet is sent completely independently of all others, e.g. if greedy routing fails and the recovery mechanism forwards the packet along a very long path even though a much shorter exists, all subsequent packets will follow the longer path. The protocols have no way to adapt and to learn from experiences.

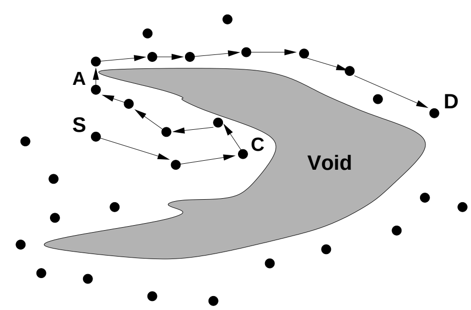

Fig. 1. Suboptimal path taken by position-based routing protocol

We can summarize these facts by saying that the statelessness of position-based protocols is not only the reason for their advantages over topology-based protocols, but is also the source of new drawbacks. While statelessness about existing path is advantageous, it is not for the topology of the network on a large scale. Thus, if we assume that the overall node distribution in the network remains quite static and only varies slowly over time, it is beneficial to accumulate such information at the nodes to facilitate communication with distant nodes.

We propose the Mobile Routing Architecture (MRA) whose objective is to overcome these aforementioned drawbacks of conventional position-based protocols. It is designed for routing in large wireless multihop networks with possibly tens of thousands of nodes with irregular topologies. In such scenarios, MRA is able to find more optimal paths than other position-based protocols by memorizing past traffic such that packets are not routed necessarily directly towards the destination anymore. The required memory to keep track of the traffic can be kept small, in the order of some hundred

The work presented in this paper was supported (in part) by the National Competence Center in Research on Mobile Information and Communication Systems (NCCR-MICS), a center supported by the Swiss National Science Foundation under grant number 5005-67322.

bytes, by applying an aggregated and fisheye-like view on the network. Furthermore, if only few data traffic is in the network and existing paths are not known, additional explorer packets can be emitted to actively discover shorter paths. Both types of packets, data and explorer packets, increase the probability for their traveled path depending on the encountered quality. Thus, packets are attracted to travel good path already traveled by other packets, which in turn increase the probability for these paths even more.

This principle of self-reinforcing of traveled paths through packets is basically the principle of ant-colony optimization [6] where ants find shortest paths between the nest and a food source. The ant colony optimization principle has been applied lately to routing in ad-hoc networks in several papers [7], [8], [9]. All these ant-based routing algorithms are similar to other topology-based protocols and have a route discovery, a route maintenance, and a route error phase such as AODV [1] and DSR [10]. They mainly make use of the ant colony optimization to improve the resilience and reliability of paths or to improve existing paths compared to other topology-based protocols. Therefore, they still have the same characteristics of other topology-based protocols such as large control traffic overhead and, thus, are not suited for large networks with highly dynamic topologies as considered in this paper.

The remainder of this paper is organized as follows. In Section II, we describe the architecture MRA and the used protocols in detail. MRA is evaluated in Section III by simulations and finally Section IV concludes the paper.

II. The Mobile Routing Architecture (MRA)

MRA is a two-layered framework with three independent protocols rather than an actual routing protocol. Three specific protocols are presented exemplarily within the MRA framework. The two protocols used on the upper layer are called Topology Abstracting Protocol (TAP) and Mobile Routing Protocol (MRP). Straight Packet Forwarding (StPF) is situated on the lower layer and functions as an interface to the physical network for MRP. Due to lack of space only the general concepts are given in this section, for more detailed information cf. to [11], [12].

A. Topology Abstraction Protocol (TAP)

TAP is the key to make routing scalable and provides in a transparent manner an aggregated and static topology with fixed "logical routers" (LR) and fixed "logical links" (LL) to MRP. Logical routers are fixed geographical areas of equal size arranged in a grid to cover the whole area. Depending on its current position, each node is part of one specific logical router. A node can easily detect, based on its position, when it crosses the border of the current logical router and then it automatically becomes a member of the new logical router. In order to scale to large networks, each logical router groups other logical routers into zones $Z_{i,j}$ as shown in Fig. 2. The zone size increases exponentially with the distance i to the center router and allows covering large areas with few zones. This is justified by the circumstance that in the view of a fixed node, close-by nodes that move some distance may be located in an entirely different direction, whereas the same movement of a node far away only marginally affects the direction. It is important to notice that the view of zones is relative. Each logical router resides in the center of its own zone model.

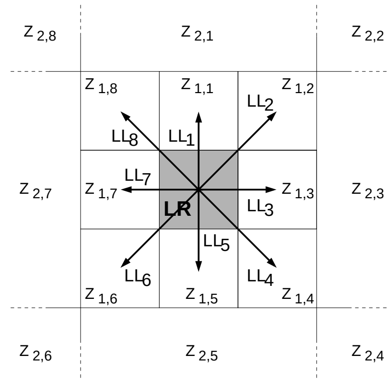

Fig. 2. Logical router LR in the center, the zones in its view $Z_{i,j}$, and its logical links LL_k indicated as arrows

A logical link LL_k represents a path along a straight line to an adjacent logical router over possibly multiple physical hops. In this way, we introduce a static logical topology on the network independent of the actual node distribution.

B. The Mobile Routing Protocol (MRP)

The actual routing protocol MRP operates on top of this abstract topology and thus does not have to cope with changing topologies. Basically, all what MRP has to do now is that whenever a node receives or overhears a packet, it determines where the packet originates from and from which direction it arrived. More precisely, it determines the source zone $Z_{i,j}$ of the packet by the coordinates of the source node as given in the packet header. Note that this zone is relative to the view of the current node. Furthermore, the node determines the last logical router in which the packet was forwarded before having entered the current logical router, i.e., it determines the logical link LL_k which approximates most closely the followed path over the last few physical hops. Nodes maintain a probabilistic routing table where all the zones and the logical links are organized in rows and columns, respectively. The value of the field in the routing table corresponding to the determined zone $Z_{i,j}$ and logical link LL_k is increased. The other seven entries in the row of $Z_{i,j}$ are decreased proportionally such that the sum over all logical links in a row for a certain zone remains 1. A high value indicates that there exists a path in the direction of that logical link to the respective zone. Eventually, the best paths will emerge and MRP is able to circumvent areas with bad or no connectivity, i.e. data packets will always be routed over logical links with high connectivity such that greedy routing is possible. MRP routes data packets by determining to which zone a packet should be routed from the destination coordinates as given in the packet header. The node then selects the logical link with the highest probability to this zone. Consequently, data packets are routed logical-hop by logical-hop over the logical links, i.e. from one logical router to one of its adjacent logical routers and so on. Furthermore, explorer packets can be transmitted periodically to explore new paths if there is only few data traffic. Unlike data packets, these packets are routed purely position-based. If a node does not have a logical link with a high probability, the data packets are also routed purely position-based and adapt therefore the role of explorer packets.

In irregular topology, the logical link pointing directly towards the destination zone may often not have a high value as no packets arrive out of this direction. Consider again the same exemplarily topology as before in Fig. 3. A node S that wants to route to a destination node D does not forward the packet towards node C, because LL_3 pointing in this direction has a very low probability as no packets from zone $Z_{3,3}$ traveled over this link. S forwards the packet either over LL_1 or LL_6 because if it received data packet originating from zone $Z_{3,3}$, the packets arrived from the direction of LL_1 and LL_3. The possible paths for packets from a node D in zone $Z_{3,3}$ to S are depicted exemplarily. Thus, for any destination node located in zone $Z_{3,3}$, the packets are also routed over these two links with high probability.

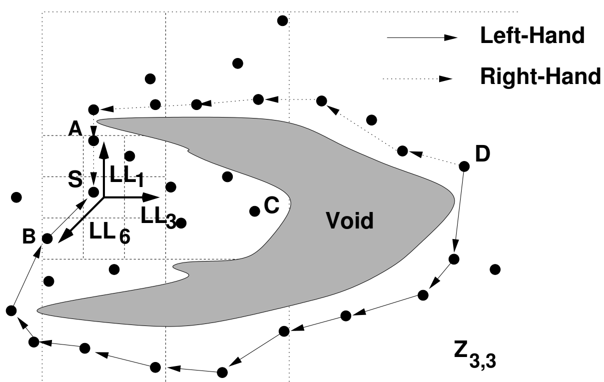

Fig. 3. Routing packets to $Z_{3,3}$ over LL_1 and LL_6

If a node moves to another logical router, its view on the network changes, and it adapts its routing table accordingly by having the probability of all logical links approaching a uniform distribution. The reason is that previously collected information about good paths looses its relevance because zones and links are relative to a node's view and do no longer correspond to previous geographical areas.

C. Straight Packet Forwarding (StPF)

StPF is a position-based routing protocol and responsible to physically forward packets over the logical link determined by MRP to the next logical router. StPF can be basically any standard position-based routing protocol. Thus, we did not design a new protocol and used instead GFG/GPSR. More advanced position-based routing protocols such as GOAFR [5], BLR [13] could also be used. In GFG/GPSR, packets are forwarded to the neighbor closest to the final destination. If no such neighbor exists and greedy routing fails, GFG/GPSR applies a perimeter routing mode to recover. Therefore, each node extracts locally a planar subgraph of the actual network graph, which is necessary to avoid loops, and forwards packets on the faces of this subgraph according to the right-hand rule. Packets are again routed in greedy mode as soon as they are received at a node that is closer to the final destination than where the packet entered the perimeter mode. More details about GFG/GPSR, the extraction of the planar subgraph, and the right-hand rule can be found in [3], [4].

III. Evaluation

We implemented and simulated MRA in a Java network simulator and compared it to GFG/GPSR and a shortest path algorithm. The Java-simulator does not account for any physical propagation medium properties or MAC layer functionality. Therefore, packets cannot be dropped due to collisions or congestion and packets do not experience delay. We use the hop count metric in order to asses the performance. Hop count metric is typically considered a good indication for the delay because CSMA based MAC protocols such as IEEE 802.11 have high cost for acquiring the medium. The nominal transmission range and the logical router side length were both set to $250\,m$. The results are average over 10 simulation runs and given with a double-sided 90% confidence interval. Data packets are transmitted periodically between two randomly chosen communication peers at a rate of 1 packet$/s$. The simulation time was set to $1800\,s$, but no data is transmitted in the initial first $900\,s$ to reach a stable state of the mobility model. MRA was always simulated with unidirectional and bidirectional traffic between the source and the destination. The reason is that MRA can use traffic flowing in the opposite direction to update the routing tables towards the destination. On the other, GFG/GPSR and the shortest path algorithm are not affected by bidirectional traffic and thus they were only simulated with unidirectional traffic. If we have bidirectional traffic between two communication peers, we consider that as having two individual traffic sources, e.g. 5 bidirectional traffic flows indicate 10 traffic sources.

A. Flat Network

Although, MRA was not designed for simple and flat network topologies, it should nevertheless perform satisfactorily in such scenarios. Therefore, we simulated 200 nodes that move according to the standard random waypoint mobility model with a speed uniformly chosen from $[1, 15]\,m/s$ and a pause time of $120\,s$ in an area of $600\,m$ x $3000\,m$. The high network density was chosen on purpose so that routing along a straight line between source and destination is possible. Traffic was transmitted between 10 randomly chosen source destination pairs and we varied the rate at which explorer packets are transmitted. In Fig. 4, the corresponding results for this scenario are depicted where the number of the explorer packets is for the whole network, i.e. with 200 nodes, 10 packets per second indicates that a node transmits an explorer packet every 20 seconds. Definitely, the shortest path algorithm yields the smallest hop count followed closely by GFG/GPSR. On the other hand, MRA suffered marginally from its non-deterministic routing policy. Packets are routed based on the probabilities given in the routing tables and may sometimes not be routed directly towards the destination. Interestingly, the number of explorer packets does not have any impact. The reason is that they are routed purely position-based between two nodes and thus only reinforce direct paths. MRA with bidirectional traffic performs slightly better because packets are less diverted by other traffic flows as the packets traveling in the opposite direction reinforce the path to their respective destinations. The reason that packets are sometimes diverted is due to mobility. Nodes have a high probability for a logical link to a certain zone, however when they move this logical link may point no longer in the correct direction. Although this effect is mitigated by the decrease of high probabilities if nodes move, packets are sometimes not routed directly towards the destination.

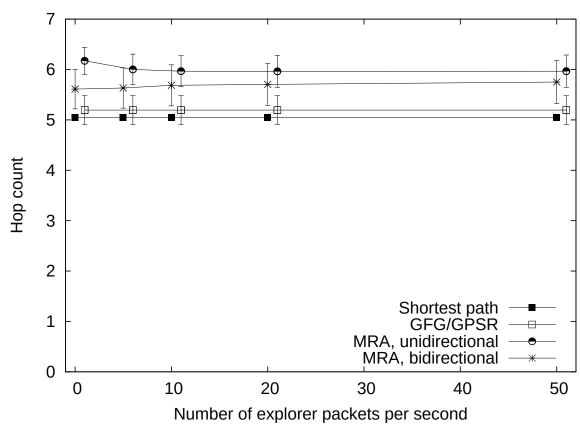

Fig. 4. Flat network scenario with varying number of explorer packets

B. Large Irregular Networks

To simulate large networks with irregular topologies, we use the restricted random waypoint mobility model [14]. The model defines rectangular city areas and highways connecting selected cities, but otherwise is similar to the standard random waypoint mobility model. Nodes choose a next waypoint within their current city or in one of the adjacent cities connected by highways. Consequently, there may be void areas with no nodes such that direct routing between some cities is not possible. A typical scenario is depicted in Fig. 5 with four cities and three highways.

We defined four cities of $1000\,m$ x $1000\,m$ interconnected by three highways with 500 nodes on an area of $3000\,m$ x $2500\,m$. Nodes in the city move at a speed in the interval $[1, 15]\ m/s$ and at a higher speed on the highway $[10, 30]\ m/s$. A typical path chosen by MRA and GFG/GPSR is also shown in the figure. Although it is definitely a worst-case scenario for GFG/GPSR, it again clearly highlights the problem of position-based protocols, namely the inability to know which are good paths to a distant node on a large scale. We first conducted simulations where the number of transmitted explorer packets was varied and we had a fixed number of traffic sources set to 10.

In Fig. 6, we can see that GFG/GPSR has on average an about 2.5 times higher hop count than the shortest possible path. Considering the fact that often the traffic flow is between

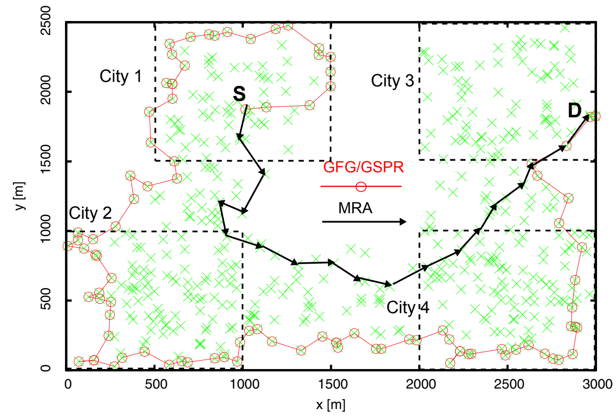

Fig. 5. Path of MRA and GFG/GPSR in irregular topology

nodes in the same city or one of the adjacent cities, we may conclude that the hop count for traffic flows between non-adjacent cities is much more than 2.5 times the shortest path. If nodes are in adjacent cities, routing along a straight line between them is possible and the performance of GFG/GPSR is almost identical to the shortest path.

MRA with only unidirectional traffic and no explorer packets performs even worse than GFG/GPSR. However, as soon as few explorer packets are transmitted the hop count drops sharply. With only 50 explorer packets transmitted per second in the whole network, i.e. with 500 nodes, each node transmits an explorer packet each 10 seconds, the hop count is about 15 compared to 10 of the shortest path and 25 for GFG/GPSR. The further increase of explorer packets does not further reduce the hop count however. On the other hand, if we have bidirectional traffic, the hop count is completely independent of the number of explorer packet. The data packets in the opposite direction are sufficient to establish high probability entries in the routing tables.

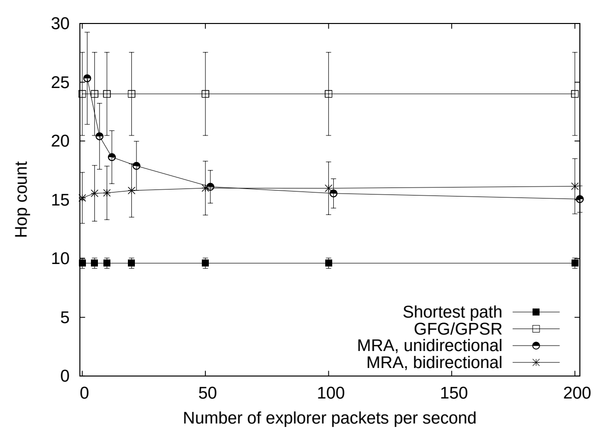

Fig. 6. Irregular network with varying number of explorer packets

In a next step, we simulated a scenario where no explorer packets are transmitted at all and only the number of traffic flows was varied Fig. 7. Again, the performance of GFG/GPSR shows an about 2.5 times higher hop count than the shortest path. Unlike before, the graphs for GFG/GPSR and the shortest path are no longer exactly constant, but only statistically constant within the confidence intervals. The reason is that, unlike the number of explorer packets, a varying number of sources may yield slightly different results among the different simulation runs. MRA with bidirectional traffic remains almost unaffected by the number of traffic flows, i.e. traffic flowing in different directions does not distort the entries in the routing tables for traffic flows to other destinations. As before where we had 10 traffic flows, MRA with unidirectional traffic suffers if we have no explorer packets and only few traffic flows. The chance that a node has overheard a lot of traffic to a given destination zone is low and, thus, the risk when it has to forward a packet to that zone is high that it forwards the packet in a wrong direction. However, as more traffic flows there are in the network, the performance of MRA with unidirectional traffic approaches the performance of MRA with bidirectional traffic. If we have sufficient traffic, the entries in the routing tables are updated accurately by the data packet themselves. The reason is that if there are no useful entries in the routing tables, data packets are routed purely position-based and thus adopt the role of explorer packets.

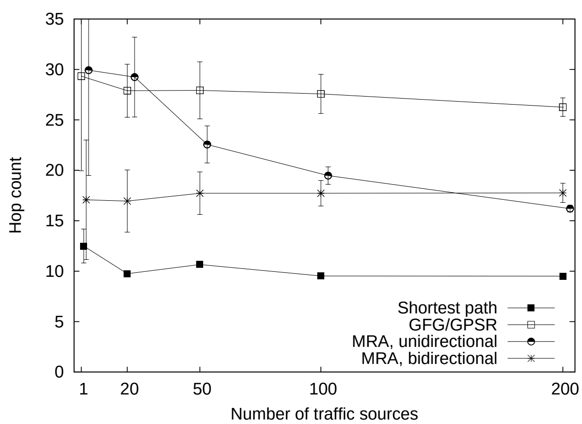

Fig. 7. Irregular network with varying data traffic and no explorer packet

IV. Conclusion

In this paper, we presented the Mobile Routing Architecture (MRA), which makes use of topology abstraction, a principle from swarm intelligence, and position-based routing. MRA is used to optimize routing in large network with irregular topologies where routing along a a straight line towards the destination is not possible. Results showed that MRA is able to cope efficiently with irregular network topologies, i.e. realistic topologies for large networks. In a scenario with a horseshoe-like topology, MRA was able to find paths that are up to 40% shorter than of GFG/GPSR. Consequently, MRA would also yield much shorter delays and reduce congestion in the network. In simple and flat network topologies, MRA performed comparable to GFG/GPRS. Unlike GFG/GPSR, MRA uses explorer packets to discover new paths and, thus, introduces additional control traffic however. Simulation showed that the number of explorer packets can kept small. For scenarios with bidirectional traffic or a lot of unidirectional traffic, even no explorer packets are required. Therefore, the overhead compared to GFG/GPSR reduces to little additional memory to store the routing table. Realistic network traffic is typically bidirectional, e.g. simply because TCP is used on the transport layer. We can summarize the main features of MRA as follows.

- MRA allows nodes to learn by memorizing past traffic such that disadvantageous paths are avoided and packets are routed along paths with high connectivity.
- Due to the abstract topology, MRA can easily cope with high mobility and is scalable in terms of number of nodes and the covered geographical area of the network.
- The overhead due to explorer packets can be minimized as only few or even none are required to find good paths.

References

[1] C. E. Perkins and E. Royer, “Ad hoc on-demand distance vector (aodv) routing,” RFC 3561, Internet Engineering Task Force IETF, July 2003. [Online]. Available: http://www.ietf.org/rfc/rfc3561.txt

[2] T. Clausen and P. Jacquet, “Optimized link state routing protocol (OLSR),” RFC 3626, Internet Engineering Task Force IETF, Oct. 2003. [Online]. Available: http://www.ietf.org/rfc/rfc3626.txt

[3] P. Bose, P. Morin, I. Stojmenovic, and J. Urrutia, “Routing with guaranteed delivery in ad hoc wireless networks,” in *Proceedings of the 3th International ACM Workshop on Discrete Algorithms and Methods for Mobile Computing and Communications (DIALM ’99)*, Seattle, USA, Aug. 1999, pp. 48 – 55.

[4] B. Karp and H. T. Kung, “GPSR: Greedy perimeter stateless routing for wireless networks,” in *Proceedings of the 6th Annual ACM/IEEE International Conference on Mobile Computing and Networking (MOBICOM ’00)*, Boston, USA, Aug. 2000, pp. 243–254.

[5] F. Kuhn, R. Wattenhofer, and A. Zollinger, “Worst-case optimal and average-case efficient geometric ad-hoc routing,” in *Proceedings of the 4th ACM International Symposium on Mobile and Ad Hoc Networking and Computing (MobiHoc ’03)*, Annapolis, Maryland, USA, June 2003, pp. 267 – 278.

[6] R. Beckers, J. L. Deneuborg, , and S. Goss, “Trails and u-turns in the selection of a path by the ant lasius niger,” *Journal of Theoretical Biology*, vol. 159, pp. 397–415, 1992.

[7] M. Güneş, M. Kähmer, and I. Bouazizi, “Ant-routing-algorithm (ARA) for mobile multi-hop ad-hoc networks - new features and results,” in *Proceedings of the 2nd Mediterranean Workshop on Ad-Hoc Networks (Med-Hoc-Net’2003)*, Mahdia, Tunesia, June 2003.

[8] G. Di Caro, F. Ducatelle, and L. Gambardella, “Anthocnet: An adaptive nature-inspired algorithm for routing in mobile ad hoc networks,” *European Transactions on Telecommunications, Special Issue on Self-Organization in Mobile Networking*, vol. 16, no. 2, 2005.

[9] M. Roth and S. Wicker, “Termite: Ad-hoc networking with stigmergy,” in *Proceedings of IEEE Global Telecommunications Conference (GLOBECOM’03)*, San Francisco, USA, Dec. 2003.

[10] D. B. Johnson, D. A. Maltz, and J. Broch, “DSR: The dynamic source routing protocol for multihop wireless ad hoc networks,” in *Ad Hoc Networking*. Addison-Wesley, 2001, ch. 5, pp. 139–172.

[11] M. Heissenbüttel, “Networking in ad-hoc networks,” Ph.D. dissertation, University of Bern, CH-3012 Bern, Switzerland, June 2005.

[12] T. Huber, “Ant-based mobile routing architecture in large-scale mobile ad-hoc networks,” Diploma Thesis, University of Bern, Jan. 2005.

[13] M. Heissenbüttel, T. Braun, T. Bernoulli, and M. Wälchli, “BLR: Beacon-less routing algorithm for mobile ad-hoc networks,” *Elsevier’s Computer Communications Journal (Special Issue)*, vol. 27, no. 11, pp. 1076–1086, July 2004.

[14] L. Blazevic, J.-Y. Le Boudec, and S. Giordano, “A location based routing method for mobile ad hoc networks,” *IEEE Transactions on Mobile Computing*, vol. 5, no. 1, Mar. 2005.