BLR: Beacon-Less Routing Algorithm for Mobile Ad-Hoc Networks*

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Routing of packets in mobile ad-hoc networks with a large number of nodes or with high mobility is a very difficult task and current routing protocols do not really scale well with these scenarios. The Beacon-Less Routing Algorithm (BLR) presented in this paper is a routing protocol that makes use of location information to reduce routing overhead. However, unlike other position-based routing protocols, BLR does not require nodes to periodically broadcast Hello-messages (called beaconing), and thus avoids drawbacks such as extensive use of scarce battery-power, interferences with regular data transmission, and performance degradation. BLR selects a forwarding node in a distributed manner among all its neighboring nodes with having information neither about their positions nor even about their existence. Data packets are broadcasted and the protocol takes care that just one of the receiving nodes forwards the packet. Optimized forwarding is achieved by applying a concept of Dynamic Forwarding Delay (DFD). Consequently, the node which computes the shortest forwarding delay relays the packet first. This forwarding is detected by the other nodes and suppresses them to relay the same packet any further. Analytical results and simulation experiments indicate that BLR provides efficient and robust routing in highly dynamic mobile ad-hoc networks.

1. Introduction

A wireless mobile ad-hoc network operates without any centralized administration and does not rely on any fixed infrastructure. Instead the network is completely self-organizing and the communication is maintained on a peer-to-peer basis between the mobile hosts. If two hosts that wish to communicate are not within range, other intermediate nodes act as relay stations.

Due to the mobility of the nodes, changes to the network topology may be frequent and unpredictable. Furthermore, nodes may suddenly be switched on/off, causing new links to appear and established links to vanish. Routing in such a dynamic environment is a difficult task and has been subject of extensive research over the past years. Several routing protocols have been defined within MANET [1] working group of IETF such as AODV [2], DSR [3], TORA [4], DSDV [5], TBRPF [6], OLSR [7], ZRP [8], FSR [9], LANDMAR [10]. These protocols either use a kind of flooding to detect routes on-demand or proactively maintain routing information at each node. Generally, they are considered not to scale in networks with more than several hundred nodes. Unlike these topology-based routing protocols which do not make use of location information, position-based (also called geometric or directional routing) protocols try to optimize routing by making use of geographical information available at each node (GFG [11], GPSR [12], LAR [13], TRR [14], AFR [15], EASE [16], DREAM [17]). Every node is aware of its own position and is notified of its neighbors' positions through the exchange of beacons (small packets broadcasted by the neighbors to announce their position). Additionally, a node is able to determine the location of the destination through a location management scheme.

This additional position-information allows improving routing significantly and, thus, increases

*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.

the network scalability in terms of network size, mobility, and traffic. Position-based routing is likely one of the enablers for large-scale mobile ad-hoc networks, where the number of nodes can potentially reach several thousands as considered in the Terminodes project [18]. (Even though, it was shown in [19] that the per node capacity tends to zero as the number of nodes goes to infinity for certain network and traffic models.)

The Beacon-Less Routing algorithm (BLR) described in this paper performs routing in a distributed manner without information about neighboring nodes. If a node has a packet to send, it broadcasts the packet and every neighboring node receives it. The protocol takes care that just one of these nodes relays the packet. This is accomplished by computing a Dynamic Forwarding Delay (DFD) at each node depending on its position relative to the previous and the destination node. The node located at the "optimal" position introduces the shortest delay and thus transmits the packet first. Other nodes recognize the occurrence of the relaying and cancel their scheduled transmission of the same packet. Avoiding periodical transmission of beacons provides many advantages, such as conserving scarce battery power and avoiding interferences with regular data transmission. To ensure that all nodes detect the forwarding, only nodes within a certain area apply DFD and take part in the contention to forward the packet.

The remainder of this paper is organized as follows. First, an overview of existing position-based routing protocols is given. The routing algorithm BLR is introduced in section 3 and also some variations and optimizations are discussed. In section 4, the basic greedy algorithm is evaluated analytically. Performance and behavior of BLR are evaluated in section 5 through simulations and compared to other position-based routing algorithms. Finally, section 6 and 7 conclude this paper.

2. Related Work

Most of the position-based routing algorithms do not require the establishment of any route prior to data transmission. A packet can be sent in a greedy manner to any intermediate node into the direction of its destination, making almost stateless routing feasible. (Exceptions are LAR [13] and DREAM [17] where location information is used in order to reduce flooding for finding a route to the destination.) Nodes neither have to maintain installed routes nor to store routing tables. Position-based routing protocols proposed in the literature mainly differ in the way they select the next hop among the neighboring nodes and in the recovery strategy in case the greedy forwarding fails. (Overviews can be found in [20], [21].) A further advantage is that position-based routing naturally supports geocasting ([22], [23], [24]).

The first position-based routing protocols (MFR [25], NFP [26], RPM [27]) were already proposed in the 1980s for packet radio networks and were lately rediscovered for mobile ad-hoc networks. These approaches are based on the notion of the term progress p. Progress is defined as the projection of the distance traveled over the last hop from P to any node A onto the line from P to the final destination D. MFR [25] was introduced trying to minimize the number of hops by selecting the node with the largest progress from the neighbors (A in Fig. 1). Under the assumption that nodes are able to adjust their transmission power, NFP was proposed in [26] in order to minimize the interference with other nodes and the overall power consumption by transmitting to the nearest node with forward progress (B in Fig. 1). In [28], an approach very similar to MFR is introduced where the packet is forwarded to the nearest node among the neighboring nodes, which are closer to the destination. The basic greedy algorithms described above are inherently loop-free, but may fail to find a path even if there exists one, e.g. in the case a packet gets stuck at a node that does not have a neighbor closer to the destination or with forward progress.

Compass routing algorithms were introduced in [29] where the forwarding decision in based on the angles between nodes. A packet is forwarded to the neighboring node minimizing the angle between itself, the previous node, and the destination (e.g. B in Fig. 1). Randomized compass [29] or greedy compass [30] are further variations of

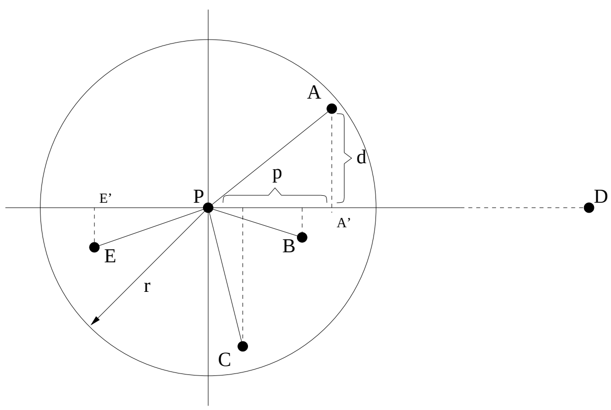

Figure 1. Forwarding Strategies

compass routing. With compass algorithms, a packet can not get stuck anymore, but they do only guarantee loop-freedom for certain kind of network graphs.

GFG [11], GPSR [12], AFR [15] and GRA [31] try to overcome these drawbacks by applying greedy loop-free forwarding combined with a recovery strategy if a packet gets stuck.

In all these position-based routing approaches, the minimum information a node must have to make useful routing decisions is its position (provided by GPS, Galileo, etc.), the position of its neighbors (through beaconing), and the final destination's location (e.g. VHR [32], GLS [33], [34]).

The drawbacks of beaconing can be broadly classified in two categories. The first category comprises drawbacks referring to energy consumption of beaconing on a physical level. Beaconing is the proactive component of position-based routing and thus occurs independently of actual data traffic. It uses scares battery-power for transmitting, receiving, and processing of beacons and also disturbs sleep cycles of nodes. (It was shown ([35], [36]) that the ratio of sending/receiving/idle listening is in the order of 2/1.5/1 for actual WaveLAN cards, i.e. substantial energy may only be saved in sleep modes. Even though the additional cost of transmitting beacons is almost negligible, beaconing nevertheless interrupts sleep cycles.) The second category consists of drawbacks on the MAC- and network-layer. First, due to the periodical broadcast of beacons, collisions with data packets are likely to occur. Second, the routing algorithm operates on the topology as perceived through the position-information provided by beacons. However, this information may be outdated or inconsistent causing the algorithms to take suboptimal decisions. For example, a node (i.e. the routing protocol) chooses a node as next hop from its neighbor table even though this node has meanwhile left its transmission range. Even in the absence of any movement, a neighboring node may only be reachable every once a while because of time-varying transmission ranges due to changing SINR (Signal to Interference and Noise Ratio). In both cases, the MAC-layer is unable to deliver the packet. Depending on the implementation, the MAC-layer tries to retransmit the packet several times after a time-out (e.g. the default value is 7 times in 802.11) and only now notifies the network layer of the failed forwarding. The network layer is then responsible to select another next hop. Preliminary results (not shown in this paper) obtained by simulations show that these effects cause a strong degradation of the performance of the network in terms of delay and packet-delivery ratio.

Lately, a new class of position-based routing algorithms were introduced (BLR [37]†, CBF [38], IGF [39]) that avoid having beacons transmitted periodically and, hence, eliminating the belonging drawbacks. The mechanism that allows selecting one neighbor as next hop in a completely distributed manner without having knowledge of the neighboring nodes is achieved in all the papers by applying the concept of DFD. They mainly differ in the investigated aspects. In CBF [38] and IGF [39], the focus is on the integration of the routing protocol with the MAC-layer, namely the IEEE 802.11 protocol. [37] discusses several optimizations to the basic greedy scheme and also derives analytical properties and limitations of this new class of protocols.

The main drawbacks of these protocols are that greedy forwarding can be applied less often than in other position-based algorithms due to restrictions on the position of the next node. Some

†The paper is an earlier version of the present paper

advantages of beacon-less algorithms are lost in case a recovery procedure needs to be initiated. Therefore, these algorithms perform best in dense networks where they operate in greedy mode most of the time.

3. The BLR Protocol (Beacon-Less Routing)

3.1. Assumptions

Nodes are aware of their own position by means of GPS, Galileo, or any other positioning service [40]. GPS and Galileo allow nodes to determine their longitude, latitude, and altitude depending on the number of satellites in the line-of-sight. (For reasons of simplicity, the altitude of nodes is not considered in this paper.) Furthermore, there is a mechanism which enables the source to detect accurately enough the destination node's position ([32], [33], [34]). But, opposed to "conventional" position-based routing algorithms described in section 2, no beaconing mechanism is used to provide nodes with topological information about their neighbors.

Furthermore, there are two system-wide parameters, which are known by all the nodes. Max_delay indicates the maximum delay a packet can experience per hop, and a maximum transmission radius r. The network is modeled with the unit disk graph where nodes may communicate directly if their distance is smaller than the fixed r. As a consequence, all links are bidirectional and antennas are omnidirectional.

3.2. Basic Principle

If a source node has a data packet to send, it first determines the position of the destination and stores these geographical coordinates along with its own current position in the header of the packet. All intermediate nodes just replace the previous node's position by their current position in the header before forwarding the packet. Since a node does not possess knowledge of neighboring nodes, it broadcasts the packet to all neighboring nodes. Upon the reception of a packet, the only available information an intermediate node has is its own position and the position of the previous and the destination node, extracted from the packet header. Thus, a node can easily derive if it is located within a specific area relative to the previous transmitting node.

Nodes located within this forwarding area apply Dynamic Forwarding Delay (DFD) prior to relaying the packet, whereas nodes outside this area drop the received packet. The value of the DFD $[0, Max\_Delay]$ depends on the relative position coordinates of current, previous, and destination node. Eventually, the node which computed the shortest DFD forwards the packet first. Every node in the forwarding area detects the further relaying of the packet and cancels its scheduled transmission of the same packet. Furthermore, passive acknowledgments are used (cp. [41]). The previous transmitting node also detects the further relaying of the packet and thus concludes that it was successfully received by another node. Thereby, acknowledgments on the MAC-layer can be avoided. (For example in IEEE 802.11, there are even no acknowledgments provided for broadcast packets.)

The algorithm continues until the destination is reached. The only node that has to send an acknowledgement is the destination node since it does not relay the packet any further. To cope with position inaccuracies of the destination position, an adapted and restricted reactive protocol based on AODV [2] is applied in the vicinity of the destination (see section 3.6).

3.2.1. Forwarding Areas

Forwarding areas are relative to the relaying node and may be basically of any shape provided that all nodes within the area are within each others transmission range. (This requirement may be dropped in cases where packet duplication is desired to increase redundancy and resilience.) An infinite number of areas fulfill this requirement. However, the forwarding area should be large in order to increase the probability of finding a node within the area. Furthermore, another objective of the area is to favor nodes that are located near the border of the transmission range, which enables large progress per transmission and thus reduces the number of hops to the destination.

In Fig. 2, three possible areas are depicted, namely a sector, a Reuleaux triangle and a circle, which all fulfill the condition of mutual possible reception for nodes located within these areas. For the sector and the Reuleaux triangle this is achieved by an apex angle of 60°, which limits the distance of two arbitrarily placed nodes to the transmission range r. The circle just has a diameter of r. The numbers in Fig. 2 indicate the ratio covered with the corresponding forwarding area to the overall transmission area. We will see in section 4 that this value and as well as the shape of the area have a strong impact on the behavior of the algorithm.

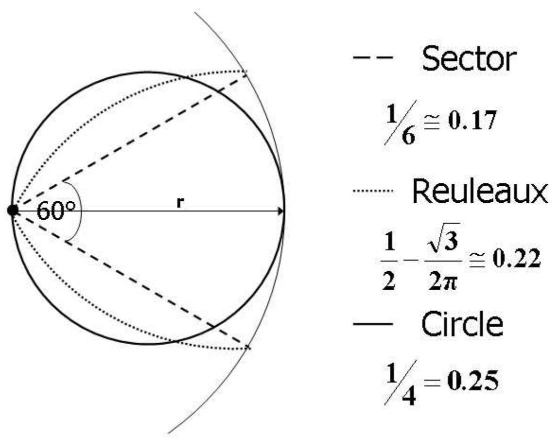

Figure 2. Different Forwarding Areas

3.2.2. Delay Functions

The function that computes DFD timer values of individual nodes may apply different forwarding policies. Each node within the forwarding area first determines different parameters, such as its progress p towards the destination with respect to the last hop and its distance d from the line $S-D$ (cf. Fig. 1). From these values the node derives the DFD value *Add_delay* in the interval $[0, Max\_delay]$.

Three different delay functions are described below. The function in (1) implements basically MFR [25]. A node with less progress introduces a larger delay than a node with more progress. Consequently, the node with the most progress within the forwarding area forwards the packet at first in order to minimize the number of hops to the destination.

- $$Add\_delay = Max\_delay \cdot \left(\frac{r-p}{r}\right) \quad (1)$$
- $$Add\_delay = Max\_delay \cdot \left(\frac{p}{r}\right) \quad (2)$$
- $$Add\_delay = Max\_delay \cdot \left(\frac{e^{\sqrt{p^2+d^2}}}{e}\right) \quad (3)$$

The function in (2) implements a slightly modified NFP [26]. NFP is not directly applicable since a node does not know which neighbor is the nearest. The node with the least progress introduces the shortest delay and forwards the packet. The objective is to reduce energy consumption and increase the number of possible simultaneous transmissions which increases the overall capacity of the network as show in [26].

Instead of these basic functions, more advanced DFD functions are possible that not only take into account the progress of a node but as well the distance to the previous node. If progress is used as the only parameter, nodes located far away from the direct line $S-D$ to the destination may be favored over a node with only little less progress but in almost straight direction towards the destination. Furthermore, it was shown in [42] that exponentially distributed random timers can further reduce the number of responses compared to uniformly distributed timers. In (3), these observations are combined to a more advanced DFD function.

In Fig. 3, the additional delay introduced by (3) for all nodes with forward progress is depicted. Nodes close to the previous node introduce a short delay, whereas nodes located farther away compute a higher DFD timer.

3.3. Unicast Packets

Broadcasting of all data packets has several drawbacks. First, broadcast packets need to be passed to the protocol stack at each receiving node and cannot be dropped at the network interface card. Furthermore, data packets are broadcasted at full transmission power, even in case the

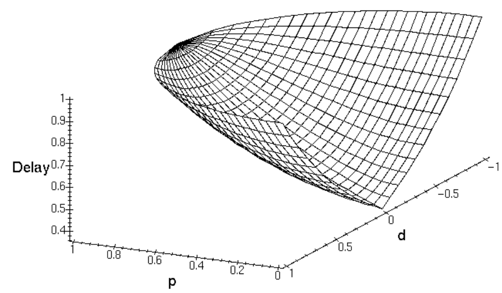

Figure 3. Additional Delay vs. Progress vs. Distance

forwarding node is located very close. Therefore, the possible interference range is increased and inhibits other simultaneous transmissions in the vicinity. These two facts are a major source of energy consumption. Furthermore, broadcast packets are transmitted at 2 Mbps while unicast packets may be transmitted at 11 Mbps using IEEE 802.11b. In order to circumvent these drawbacks, an option in BLR is not to broadcast all data packet, but to transmit most of the packets via unicast with adjusted transmission power.

After a node has detected through passive acknowledgment the successful reception of the transmitted packet, it is aware of the forwarding node's position. Thus, the node may adjust its transmission power and send the subsequent packets via unicast to the node which relayed the broadcast packet. Due to the mobility of the nodes, a node located at a better position towards the destination may enter into the node's transmission range. In order to be able to detect this new node, a packet is broadcasted at full power again after a certain time called *Beacon_Interval*. After broadcasting a packet at full power, new neighboring nodes may be detected. However, this restriction applies as well for "conventional" beaconing mechanisms, where a node located at a better position can only be detected after it announces its position by broadcasting a beacon. Hence, an optimized routing path is determined after the beacon interval.

Packets transmitted via unicast are forwarded immediately without introducing an additional delay. Furthermore, unicast packets are explicitly acknowledged on the MAC-layer. In case a node is no longer able to deliver packets via unicast because, e.g., because the downstream node was switched off, it transmits the next packet again in broadcast mode to detect other nodes towards the destination. Similarly, if a node detects its downstream node to be moving out of its transmission range, a packet is transmitted at full power even before *Beacon_Interval* in order to avoid unnecessary interruptions of links with ongoing data transmissions. Velocity and direction of movement are stored in the packet to estimate time of link break.

In order to reduce the delay in case the addressed unicast node is not reachable anymore, which would cause time-outs and retransmissions, nodes may operate in promiscuous mode, i.e. they process as well unicast packets which are not destined for them. All nodes located in the forwarding area, which detect that a unicast packet was not acknowledged or relayed within a certain time, assume that the unicast delivery failed and apply DFD as usual. There is a trade-off with energy consumption, since operating nodes in promiscuous mode consumes a lot of battery power too.

3.4. Aggregation of Paths

In order to be able to take advantage from transmitting unicast data packets, different paths through one node are aggregated. For that, each node keeps a table of all neighboring nodes and their respective positions which it gathered from overheard packets and passive acknowledgements. A node may forward a packet via unicast instead of broadcasting as soon it is aware of any neighbor that is closer to the final destination. This can possibly lead to a very suboptimal path since packets may be routed to distant nodes with little progress even if there are nodes located at much better positions. Another possibility to route the packet more directly towards the destination is to allow a node to transmit a packet only via unicast if the known neighbor is already located in the forwarding area for that packet.

3.5. Backup Mode

A node which does not detect through passive acknowledgement a forwarding of data packets within Max_delay assumes an empty forwarding area with no nodes. A recovery strategy is defined to deal with this situation. The node broadcasts a short request and all neighboring nodes reply with a packet indicating their positions. If a node located closer to the destination replies, this node is chosen as the next hop. Otherwise the actual node extracts a planar subgraph (e.g. Gabriel Graph) for its neighborhood and forwards the packet via unicast according to the right-hand rule (see e.g. AFR [15]). The extraction of the planar subgraph is necessary in order to prevent packets to enter a loop (actually this only applies for static networks). The position where the basic mode failed is stored in the packet header. As soon as the packet arrives at a node located closer to the destination than where it entered the backup mode, it switches back to the basic greedy forwarding again.

3.6. Reactive Local Routing (RLR)

In order to cope with inaccurate location information, a reactive local routing algorithm (RLR) is applied in the vicinity of the destination. The reason for using a reactive protocol instead of a proactive as proposed in Terminodes Routing [14] is that proactive protocols require to transmit a list of neighbors in the beacons. Especially in dense networks and with high transmission ranges, the number of neighbors can be large and hence significantly increase the size of the beacons.

RLR is initiated in case a node, other than the final destination node, which is within transmission range r of the destination coordinates, receives the packet and has no closer neighbor. RLR is a restricted and adapted version of the standard AODV protocol [2]. The node broadcasts six RREQs (Route Requests) for the final destination node with the destination coordinates of these RREQs in six directions separated by 60° and at twice the transmission range from the original destination coordinates. Thereby, the flooding and the propagation of the RREQs is limited. The destination node receives or at least overhears the RREQ and responds with a RREP (Route Reply). After the establishment of the path to the destination, all subsequent packets are routed directly over this route. Especially if a node has a large number of neighbors, much less packets are transmitted with RLR as opposed to sending one RREQ with a limited TTL field, which would yield at least as many transmissions as there are nodes in the x-hop neighborhood.

3.7. Node Density

Obviously, the BLR algorithm works best if it can operate most of the time in basic mode, i.e. if there is a rather high node density between the source and destination such that at least one node is located within the forwarding area. (The same applies as well for most of the other position-based routing protocols, where greedy forwarding fails in case that there is no neighboring node closer to the destination, i.e. just the forwarding area is larger.) This is often not the case due to obstacles or unpopulated areas in-between. However, some algorithms (e.g. TRR [14], MABR [43]) try to provide a path from the source to the destination, probably not along the line of sight but with some detours, such that the node density is always high along this determined path. The packets are not directly routed to the position of the destination node, but to (perhaps several) intermediate coordinates. Packets are only routed between these intermediate geographical coordinates in a greedy manner. Therefore, BLR may be advantageously integrated with these algorithms. In section 4, we will consider the impact of the node density, and also the transmission range r, on the algorithm analytically and through simulations.

3.8. Practical Considerations

The strong assumptions of the unit-disc graph model with bidirectional links and disc-like transmission areas may not hold if real physical propagation patterns and radio devices are considered. Unidirectional links are likely to exsist due to unequal SINR at the transmitting and receiving nodes. Transmission areas are highly asymmetrical due to obstacles between nodes and again due to unequal SINR, among others. Furthermore, these influences may not be static but vary over time. Because of these reasons, it is possible that a node within the forwarding area does not detect the relaying of a packet by another node. Basically, one more copy of a packet is created for each node within the forwarding area which does not detect the subsequent relaying by a next node, including the previous transmitting node. However, BLR does not introduce any additional delay since if any node in the forwarding area does receive a packet, it is forwarded almost immediately. This is unlike in traditional position-based routing protocols with beacons where the current physical conditions have a strong impact on the delay due to the outdated or inconsistent neighbor tables as discussed in section 2.

Some packets may be transmitted via unicast at 11 Mbps and others are broadcasted at 2 Mbps. It has to be taken into account that the neighbors, which receive these packets, are not the same due to the shorter transmission range at higher data rates. Therefore, if DFD timers are computed using delay function (1) such that distant nodes relay the packet first, unicast packets likely have to be transmitted at 2 Mbps as well. This problem is mitigated by applying DFD with delay function (2) such that always a close node is chosen as next hop. Conventional position-based routing protocols with beacons suffer from a similar effect since they apply forwarding strategies trying to reduce the number of hops. Beacons are broadcasted and, thus, are received at distant nodes which likely are not reachable by unicast packets at higher data rates.

4. Analytical Results

4.1. Expected Number of Hops before Basic Mode Fails

We consider a multi-hop ad-hoc network where nodes are distributed according to a two-dimensional homogenous Poisson point process, i.e. the number of nodes in a region is a random variable X depending only on the volume of the region. If n is the node density within the network (in number of nodes per square kilometer), then the probability that there are exactly k nodes appearing in a forwarding area of size $A_F(r)$, depending on the transmission range r, is given by

$$P(X = k) = e^{-n \cdot A_F(r)} \frac{(n \cdot A_F(r))^k}{k!} \tag{4}$$

This immediately yields the probability p that at least one node is located within the forwarding area.

$$p = 1 - P(X = 0) = 1 - e^{-n \cdot A_F(r)} \tag{5}$$

Furthermore, let Y be a random variable which indicates the number of hops before the algorithms fails in greedy mode, i.e. where no node is located within the forwarding area and a recovery strategy has to be applied. Y has a geometrical distribution with

$$P(Y = k) = (1 - p)p^k$$

where k is the number of successful hops. With (5), the corresponding expected value for the number of successful hops $E(Y)$ is given by

$$E(Y) = \frac{p}{1-p} = \frac{1 - P(X=0)}{P(X=0)} = \frac{1 - e^{-n \cdot A_F(r)}}{e^{-n \cdot A_F(r)}}$$

In a next step we analyze the impact of the size of the forwarding areas (i.e. sector, Reuleaux triangle, and circle) on the number of successful hops $E(Y)$. In Fig. 4, the expected number of hops in greedy mode with a transmission range of $250\,m$ is depicted as a function of the node density (in nodes per square kilometer). Even though the sizes of the forwarding areas do not vary much, it has nevertheless a strong impact on the number of hops. With $n = 80$, the number of successful hops with the circle as forwarding area is about twice and five times as high as for the Reuleaux triangle and sector, respectively. The absolute and relative difference between the three forwarding areas is even increasing for denser networks. In Fig. 5, the number of expected successful hops $E(Y)$ is shown on a logarithmic y-axis depending on the node density n and transmission radius r for the sector as forwarding area. It can be observed that the transmission range has a major influence. For small transmission ranges of $100\,m$, the greedy mode fails only after a few hops even for high

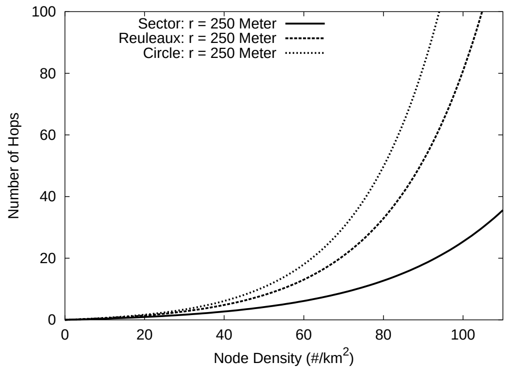

Figure 4. Number of Hops vs. Node Density

node densities. Completely unlike in the case for $r = 1000\,m$, the number of successful hops increases very strongly with only a minor increase of the node density. These conclusions apply as well to the other forwarding areas, not depicted here.

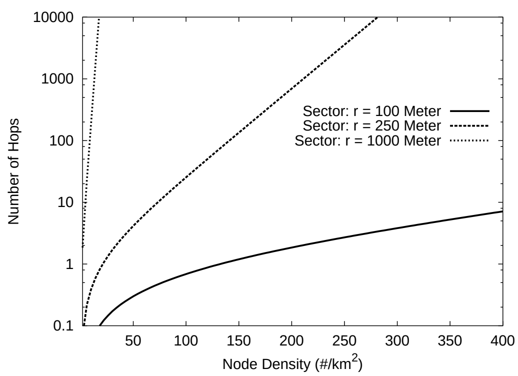

Figure 5. Number of Hops vs. Node Density

The results are similar to the observation made in [44] where the connectivity of a wireless network depending on the node density was considered. The network stays disconnected for node densities below a certain threshold and almost gets completely connected for values over that threshold.

4.2. Expected Progress in a Sector

In order to be able to calculate, e.g. the average delay per hop introduced by the algorithm, not only the Poisson distribution of the number of nodes of (4) has to be taken into account, but also the distribution of the location of the "best" node; that is, the node that computes the shortest DFD. This is due to the fact that if the number of nodes within the forwarding area is larger than 1, only the node with the minimum introduced additional delay relays the packet any further.

Since all forwarding areas are symmetrical along the line in the direction of the destination, we may consider only the upper half and assume that the transmission range is scaled to 1 without loss of generality. (cp. Fig. 6)

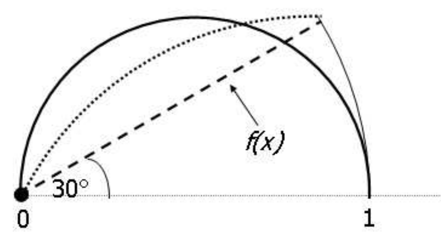

Figure 6. Normalized Forwarding Areas

(For simplicity reasons and due to lack of space, we explicitly derive here only the functions for the sector and the delay function (1). See [45] for a more detailed derivation and additional results.)

The density function for the progress X of one node located within the sector is given by $f(x)$ which describes the border of the forwarding area as depicted in Fig. 6.

$$f(x) = \begin{cases} \frac{1}{\sqrt{3}}\,x & : \quad 0 \leq x \leq \frac{3}{\sqrt{\pi}} \\ \sqrt{\frac{12}{\pi} - x^2} & : \quad \frac{3}{\sqrt{\pi}} < x \leq \sqrt{\frac{12}{\pi}} \\ 0 & : \quad \text{otherwise} \end{cases}$$

By integration, this yields the distribution function F_X.

$$F_X(t) = \begin{cases} 0 & : \quad t < 0 \\ \frac{1}{2\sqrt{3}}\,t^2 & : \quad 0 \leq t \leq \frac{3}{\sqrt{\pi}} \\ \frac{t}{2}\sqrt{\frac{12}{\pi} - t^2} & : \\ +\frac{6}{\pi} arcsin\left(\sqrt{\frac{\pi}{12}}t\right) - 2 & : \quad \frac{3}{\sqrt{\pi}} < t \leq \sqrt{\frac{12}{\pi}} \\ 1 & : \quad t > \sqrt{\frac{12}{\pi}} \end{cases} \tag{6}$$

Only the node with the most progress relays the packet. Therefore, we are interested in the distribution of the maximum function of independent and identically distributed (referred to as i.i.d.) random variables X_i $(i \leq n)$, where the density function of each X_i is given by $F_X(t)$.

The distribution of the maximum of i.i.d. random variables X_i with $(i \leq n)$ is calculated as follows.

$$\begin{aligned} F_{max_{i\leq n}\, X_i}(t) &= P(max_{i\leq n}\, X_i \leq t) \\ &= P(X_i \leq t, \forall i \leq n) \\ &= P(X_1 \leq t, \ldots, X_n \leq t) \\ &= [P(X_1 \leq t)]^n \\ &= [F_{X_1}(t)]^n \end{aligned} \tag{7}$$

The expected value $E(Z)$ for a random variable Z and its distribution function F_Z is given by

$$E(Z) = \int_0^\infty (1 - F_Z(x))\; dx - \int_{-\infty}^0 F_Z(x)\, dx$$

Together with (6) and (7), this yields for the expected progress per hop

$$\begin{aligned} E(max_{i\leq n}\, X_i) &= \int_0^{\sqrt{\frac{12}{\pi}}} [1 - (F_X(t))^n]\; dt \\ &\approx \sqrt{\frac{\pi}{\sqrt{12}}}\, \frac{2n}{2n+1} \end{aligned} \tag{8}$$

The corresponding functions for the other forwarding areas are calculated analogously. In Fig. 7, the expected progress $E(max_{i\leq n}\, X_i)$ is shown depending on the number of nodes located in the forwarding area. As expected the progress of the sector is higher than for the Reuleaux triangle and the circle since the center of gravity is located farther away from the previous node. However, the different sizes of the forwarding areas are not taken into account. From (4) and (8), we obtain the following function for the expected progress P which takes into account the node density n.

$$\begin{aligned} P &\approx \sum_{k=1}^{\infty} e^{-n\cdot A_F(r)}\, \frac{(n \cdot A_F(r))^k}{k!} \sqrt{\frac{\pi}{\sqrt{12}}}\, \frac{2k}{2k+1} \\ &= \sqrt{\frac{\pi}{\sqrt{12}}}\, e^{-n\cdot A_F(r)} \sum_{k=1}^{\infty} \frac{(n \cdot A_F(r))^k}{k!} \frac{2k}{2k+1} \end{aligned}$$

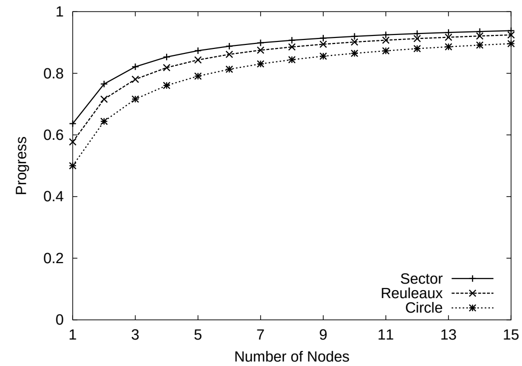

Figure 7. Expected Progress vs. Number of Nodes

In Fig. 8, the expected progress P is shown as a function of the number of neighbors of a node, which is directly related to the overall node density and the transmission range r. The progress is almost the same for all forwarding areas, independent of the actual number of neighbors.

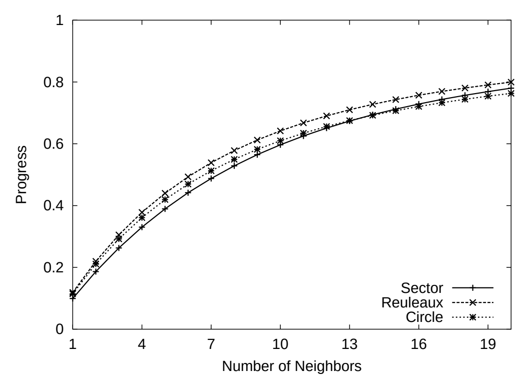

Figure 8. Expected Progress vs. Number of Neighbors

Therefore we may conclude that the best choice for the forwarding area is the circle since it gives about the same progress per hop as the other two forwarding areas, independent of the actual node density, and at the same time gives by far the highest number of successful hops before the greedy mode fails (cp. Fig. 4).

5. Performance Considerations

In this section, the concept of beacon-less routing is verified through simulations. We compare the performance of BLR to the well-know GPSR [12] and LAR1 [13] protocols. The protocols are implemented in QualNet [46], a discrete-event network simulator that includes detailed models for wireless networking. The following scenarios are configured for the performance evaluation. 200 nodes are randomly placed over a 600 x 3000 m flat terrain where the simulation lasts for 900 seconds. The rectangular shape of the simulation area is chosen to obtain longer paths, i.e. a higher average hop count. The random waypoint mobility model is applied where the speed of the nodes is randomly chosen between 1 and $40\,m/s$. (cp. [47]). There is one CBR (Constant Bit Rate) source which generates two 64 Byte UDP packets each second. The source and destination node of the CBR flow are randomly chosen among all 200 nodes. The traffic starts at $180\,s$, after the network has reached a stable average mobility, and ends at $880\,s$ such that all emitted packets arrive at the destination. On the MAC-layer, standard 802.11 DCF is applied with a nominal bit rate of 2 Mbps for broadcast and as well for unicast packets. The low traffic scenario was chosen in order to prevent congestion and reduce probability of packet collision to isolate the effects of mobility and performance of routing. The physical parameters of the antenna such as transmission power, antenna gain, and receiver sensitivity are set to obtain a nominal transmission range of $450\,m$.

The implementation of GPSR follows closely the specification as given in [12] such as support for MAC-layer failure feedback, interface queue traversal, and promiscuous use of the network interface. The beacon interval is set to $1.5\,s$ and accordingly the time-out interval to $4.5 \cdot 1.5\,s = 6.75\,s$ after which a node is deleted from the neighborhood table if no beacon is received.

The implementation of the BLR is limited currently to the basic greedy mode, i.e. all the packets are broadcasted and there is no recovery strategy in case no node is located in the forwarding area, and packets are simply dropped. In order to obtain nevertheless comparable results, we use a rather high node density (111 nodes per square kilometer.) such that BLR is able to operate (almost) only in greedy mode. The Max_Delay is set to $40\,ms$. Furthermore, the circle with radius r is applied as forwarding area and the additional delay at each node is determined through (1). In Fig. 9, the packet delivery ratio is shown for the three different protocols. The values for GPSR and LAR1 increase for lower mobility, but remain in general much lower than for BLR. BLR is able to deliver more than 99% of the packets independent of the mobility, since it does neither have to discover and maintain routes nor to maintain a neighbor table that may be outdated and inconsistent.

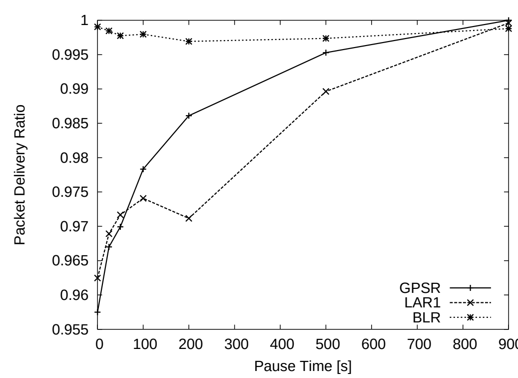

Figure 9. Packet Delivery Ratio vs. Pause Time

The results in Fig. 10 show the average end-to-end delay. Especially for high mobility scenarios, GPSR and LAR1 fail to delivery packets within reasonable time. For LAR1 this is caused by very frequent route breaks. A node along the path returns a route error message if the next hop on the route is broken, which causes the source to reinitiate route discovery for the destination and consequently delays the delivery of the data packets further. In Fig. 11, the number of generated route error messages is shown with more than 100 route discoveries for high mobility scenarios.

The delay of GPSR is mainly due to the outdated neighbor tables. The routing protocol selects a next hop in its neighbor table and the MAC-layer tries to deliver the packet to this node.

However, if this node is not reachable anymore, the MAC-layer sends a failure notification back to the network layer and the routing protocol selects another next hop. However since GPSR selects nodes that are very distant, these nodes likely have left the transmission area. In our simulations, GPSR had to select several times a next hop until finally the MAC-layer was able to deliver the packets. In Fig. 11, the numbers of RTS retransmissions due to CTS time-out are depicted. The curve is similar to the curve of the route error messages in LAR1 and both are approximately proportional to the end-to-end delay of the corresponding routing protocol.

These drawbacks vanish as nodes get less mobile and GPSR and as well LAR1 even perform slightly better than BLR for static networks, since data packets are delayed at each node in BLR. The advantage of BLR in terms of end-to-end delay is that the performance is basically independent of the mobility. Packets are delivered after approximately $30\,ms$ even for high mobility in our simulations. It is worth noting that the end-to-end delay of BLR is even less than the Max_Delay set to $40\,ms$ for one hop. Due to the high node density, the probability is high that there is always a node with a large progress within the forwarding area which computes a DFD much shorter than Max_Delay.

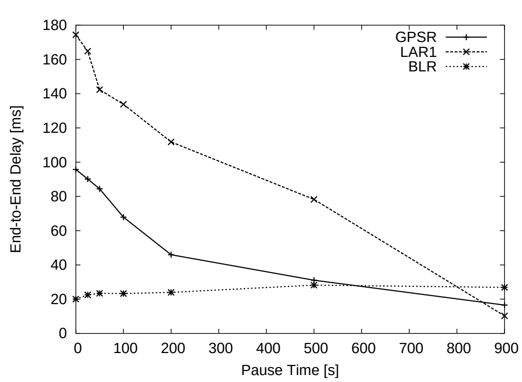

Figure 10. End-to-End Delay vs. Pause Time

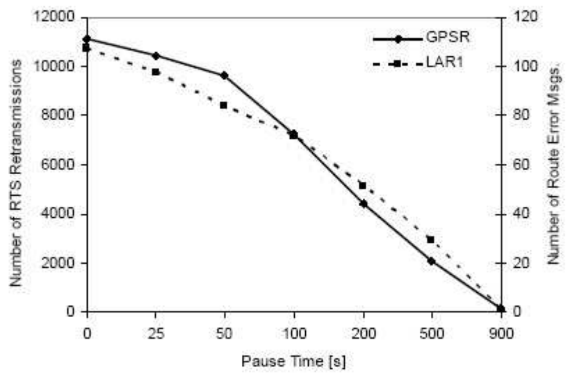

Figure 11. Route Error Messages and RTS retransmissions

6. Conclusion

Conventional position-based routing protocol suffer from several drawbacks caused by the proactive broadcasting of beacon-messages, such as outdated neighbor tables and control packet transmissions which degrade network performance. The BLR routing protocol described in this paper avoids any beaconing mechanism, i.e. nodes do not need knowledge about their neighborhood. Packets are broadcasted and the next hop is chosen in a completely distributed way by introducing a Dynamic Propagation Delay at each receiving node depending on its relative position in the forwarding area. Some limitations and fundamental properties of BLR are derived which demonstrate that network performance is highly dependent on node density and transmission range. In high node density networks or with large transmission ranges, BLR is capable of operating in greedy mode for a long time. However, since BLR operates on the actual topology and is completely stateless, the performance is almost independent of node mobility. Analytical results are supported by simulations which show a superior performance of BLR compared to GPSR and LAR1.

7. Outlook

In future works, we will extend the current implementation of the BLR protocol with options and variations discussed in this paper (backup mode, unicast packets, different forwarding areas and delay functions, etc.) in order to investigate and demonstrate different scenarios such as low node density and high traffic volume. A further direction of research is the use of directional antennas. Directional antennas seem to be well suited for BLR since only a part of the actual transmission range is used to find a next hop, namely the forwarding area. Currently, 802.11 DCF is the most widely used MAC-protocol for ad-hoc networks. The overhead introduced with the RTS-CTS-DATA-ACK dialog renders several advantages provided by BLR useless. Therefore we plan to investigate MAC-protocols adapted to our routing protocol. Multiple access schemes (e.g. CDMA) could be exploited to increase the performance and capacity of the network.

8. Acknowledgment

We would like to thank Hans U. Schmid for his valuable comments and careful review of the paper.

REFERENCES

1. (2003, Sept.) Mobile ad-hoc networks (manet) Working Group. Internet Engineering Task Force. [Online]. Available: http://www.ietf.org/html.charters/manet-charter.html
2. C. E. Perkins and E. Royer, "Ad-hoc on-demand distance vector routing," in *Proc. WMCSA '99*, New Orleans, USA, Feb. 1999, pp. 90–100.
3. 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.
4. V. D. Park and M. S. Corson, "A highly adaptive distributed routing algorithm for mobile wireless networks," in *Proc. INFOCOM '97*, Kobe, Japan, Apr. 1997, pp. 1405–1413.
5. C. Perkins and P. Bhagwat, "Highly dynamic destination-sequenced distance-vector routing (DSDV) for mobile computers," in *Proc. ACM/SIGCOMM '94 Conference on Communications Architecture, Protocols and Applications*, London, UK, Aug. 1994, pp. 234–244.
6. B. Bellur and R. G. Ogier, "A reliable, efficient topology broadcast protocol for dynamic networks," in *Proc. INFOCOM '99*, New York, USA, Mar. 1999, pp. 178–186.
7. T. Clausen, P. Jacquet, P. Muhlethaler, A. Laouiti, A. Qayyum, and L. Viennot, "Optimized link state routing protocol," in *Proc. INMIC '01*, Lahore, Pakistan, Dec. 2001.
8. Z. J. Haas and M. R. Pearlman, "A hybrid framework for routing in ad hoc networks," in *Ad Hoc Networking*. Addison-Wesley, 2002, pp. 221 – 253.
9. A. Iwata, C.-C. Chiang, G. Pei, M. Gerla, and T. wei Chen, "Scalable routing strategies for ad hoc wireless networks," *IEEE J. Select. Areas Commun.*, vol. 17, no. 8, pp. 1369–1379, Aug. 1999.
10. G. Pei, M. Gerla, and T.-W. Chen, "Fisheye state routing in mobile ad hoc networks," in *Proc. ICDCS '00*, Taipei, Taiwan, Apr. 2000, pp. 71–78.
11. P. Bose, P. Morin, I. Stojmenovic, and J. Urrutia, "Routing with guaranteed delivery in ad hoc wireless networks," *ACM/Baltzer Wireless Networks*, vol. 7, no. 6, pp. 609–616, Nov. 2001.
12. B. Karp and H. T. Kung, "GPSR: Greedy perimeter stateless routing for wireless networks," in *Proc. MOBICOM '00*, Boston, USA, Aug. 2000, pp. 243–254.
13. Y.-B. Ko and N. H. Vaidya, "Location-aided routing (LAR) in mobile ad hoc networks," *ACM/Baltzer Wireless Networks*, vol. 6, no. 4, pp. 307–321, Sept. 2000.
14. L. Blazevic, S. Giordano, and J.-Y. Le Boudec, "Self organized terminode routing," *Cluster Computing Journal*, vol. 5, no. 2, pp. 205–218, Apr. 2002.
15. F. Kuhn, R. Wattenhofer, and A. Zollinger, "Asymptotically optimal geometric mobile ad-hoc routing," in *Proc. DIALM '02*, Atlanta, USA, Sept. 2002, pp. 24–33.
16. M. Grossglauser and M. Vetterli, "Locating nodes with ease: Mobility diffusion of last en-

counters in ad hoc networks," in *Proc. INFOCOM '03*, San Francisco, USA, Mar. 2003.
17. S. Basagni, I. Chlamtac, V. R. Syrotiuk, and B. A. Woodward, "A distance routing effect algorithm for mobility (DREAM)," in *Proc. MOBICOM '98*, Dallas, Texas, USA, Oct. 1998, pp. 76–84.
18. J.-P. Hubaux, J.-Y. Le Boudec, T. Gross, and M. Vetterli, "Towards self-organized mobile ad-hoc networks: the terminodes project," *IEEE Commun. Mag.*, vol. 39, no. 1, pp. 118–124, Jan. 2001.
19. P. Gupta and P. Kumar, "The capacity of wireless networks," *IEEE Trans. Inform. Theory*, vol. 46, no. 2, pp. 388–404, Mar. 2000.
20. S. Giordano, I. Stojmenovic, and L. Blazevic, "Position based routing algorithms for ad hoc networks: A taxonomy," in *Ad Hoc Wireless Networking*. Kluwer, 2003, to appear.
21. M. Mauve, J. Widmer, and H. Hartenstein, "A survey on position-based routing in mobile ad-hoc networks," *IEEE Network*, vol. 15, no. 6, pp. 30–39, Nov. 2001.
22. R. E. Christian Maihöfer, "Virtual warning signs: A geocast enabled service for ad hoc networks," in *Proc. ASWN' 03*, Bern, Switzerland, July 2003, pp. 135–147.
23. Y.-B. Ko and N. H. Vaidya, "Geocasting in mobile ad hoc networks: Location-based multicast algorithms," A&M University, Texas, USA, Tech. Rep. TR-98-018, Sept. 1998.
24. J. C. Navas and T. Imielinski, "Geocast - geographic addressing and routing," in *Proc. MOBICOM '97*, Budapest, Hungary, Sept. 1997, pp. 66–76.
25. H. Takagi and L. Kleinrock, "Optimal transmission ranges for randomly distributed packet radio terminals," *IEEE Trans. Commun.*, vol. 32, no. 3, pp. 246–257, Mar. 1984.
26. T.-C. Hou and V. Li, "Transmission range control in multihop packet radio networks," *IEEE Trans. Commun.*, vol. 34, no. 1, pp. 38–44, Jan. 1986.
27. R. Nelson and L. Kleinrock, "The spatial capacity of a slotted ALOHA multihop packet radio network with capture," *IEEE Trans. Commun.*, vol. 32, no. 6, pp. 684–694, June 1984.
28. I. Stojmenovic and X. Lin, "Power-aware localized routing in wireless networks," *IEEE Trans. Parallel Distrib. Syst.*, vol. 12, no. 11, pp. 1122–1133, Nov. 2001.
29. P. Bose and P. Morin, "Online routing in triangulations," in *Proc. ISAAC '99*, Chennai, India, Dec. 1999, pp. 113–122.
30. P. Bose, P. Morin, A. Brodnik, S. Carlsson, E. D. Demaine, R. Fleischer, J. I. Munro, and A. Lopez-Ortiz, "Online routing in convex subdivisions," in *Proc. ISAAC '00*, Taipei, Taiwan, Dec. 2000, pp. 47–59.
31. R. Jain, A. Puri, and R. Sengupta, "Geographical routing using partial information for wireless ad hoc networks," *IEEE Personal Commun. Mag.*, vol. 8, no. 1, pp. 48–57, Feb. 2001.
32. S. Giordano and M. Hamdi, "Mobility management: The virtual home region," EPFL, Lausanne, Switzerland, Tech. Rep. SSC/1999/037, Oct. 1999.
33. J. Li, J. Jannotti, D. S. J. De Couto, D. R. Karger, and R. Morris, "A scalable location service for geographic ad-hoc routing," in *Proc. MOBICOM '00*, Boston, USA, Aug. 2000, pp. 120–130.
34. I. Stojmenovic and B. Vukojevic, "A routing strategy and quorum based location update scheme for ad hoc wireless networks," SITE, University of Ottawa, Ottawa, Canada, Tech. Rep. TR-99-09, Sept. 1999.
35. L. M. Feeney and M. Nilsson, "Investigating the energy consumption of a wireless network interface in an ad hoc networking environment," in *Proc. INFOCOM '01*, Anchorage, USA, Apr. 2001.
36. M. Stemm and R. H. Katz, "Measuring and reducing energy consumption of network interfaces in hand-held devices," *IEICE Trans. Commun.*, vol. E80-B, no. 8, pp. 1125 –1131, Aug. 1997.
37. M. Heissenbüttel and T. Braun, "A novel position-based and beacon-less routing algorithm for mobile ad-hoc networks," in *Proc. ASWN' 03*, Bern, Switzerland, July 2003, pp. 197–210.
38. H. Füssler, J. Widmer, M. Käsemann,

M. Mauve, and H. Hartenstein, “Becaonless position-based routing for mobile ad-hoc networks,” Department for Mathematics and Computer Science, University of Mannheim, Germany, Tech. Rep. TR-03-001, 2003.
39. B. Blum, T. He, S. Son, and J. Stankovic, “IGF: A state-free robust communication protocol for wireless sensor networks,” Department of Computer Science, University of Virginia, USA, Tech. Rep. CS-2003-11, 2003.
40. S. Capkun, M. Hamdi, and J.-P. Hubaux, “GPS-free positioning in mobile ad-hoc networks,” *Cluster Computing Journal*, vol. 5, no. 2, pp. 118–124, Apr. 2002.
41. J. Jubin and J. D. Tornow, “The DARPA packet radio network protocols,” *Proc. IEEE*, vol. 75, no. 1, pp. 21–32, Jan. 1987.
42. J. Nonnenmacher and E. W. Biersack, “Scalable feedback for large groups,” *IEEE/ACM Trans. Networking*, vol. 7, no. 3, pp. 375–386, June 1999.
43. M. Heissenbüttel and T. Braun, “Ants-based routing in large-scale mobile ad-hoc networks,” in *KiVS '03*, Leipzig, Germany, Feb. 2003, pp. 91–99.
44. O. Dousse, P. Thiran, and M. Hasler, “Connectivity in ad-hoc and hybrid networks,” in *Proc. INFOCOM '02*, New York, USA, June 2002.
45. M. Heissenbüttel and T. Braun, “BLR: A beacon-less routing algorithm for mobile adhoc networks,” Institute of Computer Science and Applied Mathematics, University of Bern, Switzerland, Tech. Rep. IAM-03-001, Mar. 2003.
46. (2003, Sept.) Qualnet. Scalable Network Technologies (SNT). [Online]. Available: http://www.qualnet.com/
47. J. Yoon, M. Liu, and B. Noble, “Random waypoint considered harmful,” in *Proc. INFOCOM '03*, San Francisco, USA, Mar. 2003.