A Novel Position-based and Beacon-less Routing Algorithm for Mobile Ad-Hoc Networks*

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Abstract

In this paper we present a novel routing algorithm (called BLR: Beacon-Less Routing Algorithm) for mobile ad-hoc networks in which nodes are not required to have information about neighboring nodes, neither about their positions nor even about their existence. If a node has a packet to transmit, it just broadcasts the packet. Only nodes within a certain area are potentially allowed to forward the packet. Each of these nodes introduces an additional delay depending on its position before forwarding the packet. One node eventually transmits first; the other nodes detect this subsequent forwarding of the same packet and abandon their scheduled transmission. BLR especially avoids beaconing, a broadcast mechanism to inform neighbors of a node's position, which exists to our knowledge in all other position-based routing algorithms. These mechanisms use scarce battery power, interfere with regular data transmission, and degrade the performance of the network. Analytical results and simulation experiments indicate that BLR can provide efficient and battery-conserving routing in mobile ad-hoc networks.

1 Introduction

A wireless mobile ad-hoc network consists solely of wireless hosts that are free to move randomly. These networks operate without the support of any fixed infrastructure and are completely self-organizing and self-configuring. Routing in such an environment is a difficult task due to the mobility of the nodes, which may cause frequent and unpredictable changes in the routing topology.

A lot of routing protocols, which do not make use of any location information were designed for rather small networks with up to some hundred nodes. Most of them hardly scale with large mobile ad-hoc networks, since they either use a kind of flooding to detect routes on-demand (e.g. AODV, DSR, TORA), try

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to maintain pro-actively routing information (e.g. DSDV, OLSR, TBRPF), or combine both of these approaches (e.g. ZRP). (An overview can be found in [1].)

The availability of small and cheap GPS-receivers is one of the key enablers for position-based routing (also called geometric or directional routing) in mobile ad-hoc networks. Every node is aware of its own position and is notified of its neighbors' positions through beacons (small packets broadcasted by the neighbors to announce their position). Additionally a node is able to determine the location of the destination through any location management service (e.g. VHR [2],GLS [3]). This additional geographical information allows improving routing significantly especially for large-scale mobile ad-hoc networks where the number of nodes can potentially reach several thousands or even millions such as considered in the terminodes project [2]. These three kinds of position information are as well considered as the minimum information a node must have to make useful routing decisions.

In LAR and DREAM location information is used in order to reduce flooding for finding a route to the destination. A lot of position-based routing algorithms even do not require the establishment of any route prior to data transmission (e.g. AFR, GPSR, GRA, GFG, Compass and Randomized Compass. Overviews can be found in [4] and [5] and references therein.) A packet can just be sent to any intermediate node into the direction of the destination, making almost stateless routing feasible. In this way, nodes neither have to keep track of installed routes nor to store routing tables. A further advantage is that position-based routing naturally supports geocasting.

In this paper, we describe an algorithm called BLR (Beacon-Less Routing algorithm) that allows dropping the assumptions that nodes have to know their neighbors' positions to make useful routing decisions. In this way, the periodical advertisement of each node's position by sending beacons can be avoided. A node does neither need to have knowledge of its neighbors' positions nor even of their existence. If a node wishes to send a packet, it just broadcasts it and every neighboring node receives it. The protocol takes care that just one of these nodes relays the packet any further. This is accomplished by introducing a small additional delay at each node depending on its position relative to the previous node and the destination. The node located at the most "optimal" position introduces the fewest delay and thus transmits the packet at first. The other nodes detect this subsequent relaying and cancel their scheduled transmission.

In independent work [6], a very similar approach called CBF is proposed which supports the results presented herein. The two approaches differ mainly in the way they recover in case the basic forwarding strategy fails.

The remainder of this paper is organized as follows. First, the network model and as well some terms and notions are described briefly. In section 3 the routing algorithm BLR for mobile ad-hoc networks is introduced and as well some variations and optimizations are discussed. The basic algorithm is evaluated analytically in section 4. These results are then compared in section 5 with measurements obtained through simulations. Finally section 6 concludes the paper.

2 Preliminaries

The notion of the term progress was introduced in [7]. Progress is defined as the projection of the distance traveled over the last hop from P to any node onto the line from P to the final destination D (e.g. A', B', C', E' in Fig. 1).

We use the unit graph model and thus presume bidirectional links and omni-directional antennas. Like for the other position-based routing algorithms discussed in the previous section, we assume that nodes are aware of their own position and that there is any mechanism which enables the source to detect accurately enough the destination node's position. But as opposed to other position-based routing algorithms, we do not assume that a node needs to have information about its neighboring nodes.

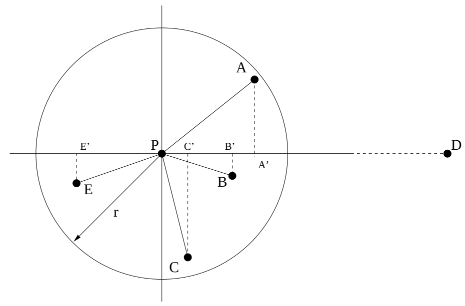

Figure 1: Progress of nodes A,B,C,E

The positions of the destination and the previous transmitting node are stored in the packet header. Furthermore, there are two system-wide parameters, which are known by all the nodes. Max_delay indicates the maximum delay a packet may perceive per hop and r the (maximal) transmission radius.

3 The BLR-Algorithm (Beacon-Less Routing)

3.1 Basic Mode

The main feature is the absence of any beaconing mechanism. Beacons are small data packets broadcasted by a node to inform its neighbors of its position. Consequently, a node does normally not have any information about its neighbors. The algorithm takes care that an appropriate neighboring node is chosen to forward the packet. First, the source node determines the destination node's position prior to the transmission and stores these geographical coordinates in the header of the packet. From then on, basically every node, whether it is the source or any intermediate node, performs exactly the same algorithm to forward the packet. A node stores its position in the packet header and just broadcasts the packet. Several neighbors around the transmitting node receive the packet.

The only available information a node has upon the reception of a packet is the position of the previous and the destination node from the packet header, and as well its own position. In this way, a node can easily determine if it is located within a 60° sector from the previous node's position towards the destination location with a radius that just equals the transmission range r. The angle of 60° results from the precondition that each node within this sector should be able to detect the transmission of any other node within this sector for the algorithm to work properly, as described below. Only nodes within this sector are taking part in the elimination process to forward the packet (e.g. nodes A and B in Fig. 2). The other nodes just discard the packet (e.g. nodes C and E).

Among the nodes which are located in the 60° sector within the transmission range r, the one with the most progress is eventually chosen (i.e. node A). This is accomplished through the following mechanism. Each node within this 60° sector determines its progress p towards the destination with respect to the last hop. From this value it derives a value Add_delay in the interval $[0, .., Max\_delay]$ which indicates the delay additionally introduced before relaying the packet.

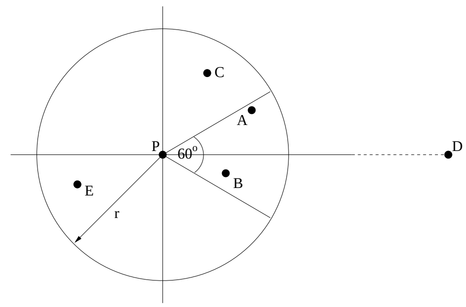

Figure 2: Forwarding in 60° Sector

$$Add\_delay = Max\_delay \, \frac{r - p}{r} \tag{1}$$

A node with less progress introduces a larger delay than a node with more progress. Consequently, the node with the most progress within this 60° sector forwards the packet at first. Since two nodes within this sector are located at a maximum distance of r away from each other, every node in the sector overhears the further relaying of the packet and cancels its scheduled transmission of the same packet, since obviously another node is located at a "better" position. Furthermore, we make use of passive acknowledgments (cp. [8]). The previous node detects the further relaying of a packet as well and thus concludes that its transmission was successfully received by another node. In this way, the need to have acknowledgments on the MAC-Layer is avoided.

3.2 Backup Mode

If a node does not detect a further forwarding of its previously broadcasted packet within Max_delay, it assumes that no node is located within the 60° sector towards the destination. In this case, the BLR algorithm switches to backup mode which provides a fallback mechanism to recover from this state. The position where the basic mode failed is stored in the packet header as well. 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 mode again.

The packet is retransmitted in backup mode and each receiving node introduces again a delay in the interval $[0, .., Max\_delay]$, but this time solely depending on the angle α between itself, the previous node, and the destination.

$$Add\_delay = Max\_delay \, \frac{\alpha - 90^o}{360^o} \tag{2}$$

With this delay function any node with forward progress relays the packet before any node with backward progress in a clockwise order. Normally not all the neighboring nodes are able to detect a transmission of any arbitrary other neighboring node with this method. Therefore unlike in the basic mode, the previous node transmits a control packet as soon as it detects the forwarding of the data packet through another node to inform the other neighboring nodes of the successful forwarding and prompts them to abandon their scheduled transmission.

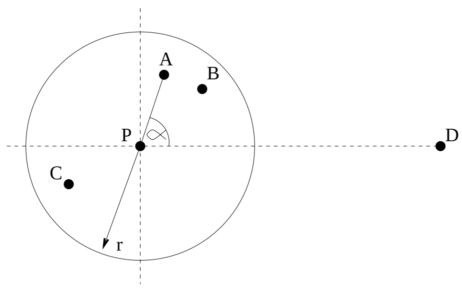

Figure 3: Clockwise retransmission

For example consider Fig. 3 where P transmits a packet in backup mode that is successfully received at A, B, and C. Due to the new delay function in (2), node A introduces the smallest additional delay and thus relays the packet first. Node B detects this forwarding and cancels its transmission. However, node C is out of transmission range of A and is not able to detect the forwarding directly. But it is notified through the additional control packet transmitted by P.

3.3 Extensions

3.4 Unicast Packets

Not all the packets need to be broadcasted at full power in order to save scarce battery-power. After a node detects through passive acknowledgment that another node forwarded the packet, it is automatically aware of that node's position as well. Therefore it is not necessary to transmit subsequent packets with the same destination with full power all the time. The node adjusts its transmission power and sends the subsequent packets per unicast to the node which relayed the last broadcasted packet and only every, e.g., three seconds (this parameter is called *Beacon_Threshold*), a packet is broadcasted at full power in order to detect possibly other nodes located at a better position towards the same destination. Furthermore, the packets transmitted per unicast are forwarded immediately without introducing an additional delay.

Actually, the *Beacon_Threshold* does not need to be a time interval. It may indicate as well a threshold for the traveled distance, the number of link incidents, etc. after which a packet has to be sent at full power again (cp. [9]).

3.4.1 Node Density and Interaction with other Protocols

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 almost always at least one node is located within the 60° sector. (Something similar also holds for most of the other position-based routing protocols where greedy forwarding fails and a fallback mechanism has to be applied in case that there is no neighboring node located at a more optimal position.) This is often not the case due to obstacles or unpopulated areas in-between. However, there exist algorithms (e.g. TRR [2], MABR [10]) which 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, and the packets are only routed between these intermediate geographical coordinates in a greedy manner.

3.4.2 Position Inaccuracies

We distinguish between two kinds of inaccuracies. The first kind arises from the fact that the location information about the destination which the source retrieved by the location management service may not be accurate anymore since the destination node has moved since then. To deal with this situation, we propose to use a slightly modified on-demand routing scheme (e.g. AODV, DSR) in the vicinity of the destination. Therefore when a packet gets close to the destination and cannot be delivered to the final destination by using geographical routing, an intermediate node broadcasts a route request packet with a limited time-to-live field which is acknowledged by the destination with a route reply.

The second kind may occur in case a node is not able to determine exactly its position. Thus, a node may conclude misleadingly that it is located within the 60°-sector for a received packet where it is not. In this way it is not further guaranteed that the complete area of nodes is covered by the subsequent broadcast. Therefore a packet may be duplicated if the forwarding remains undetected at some nodes. In the reverse situation where a node determines wrongly its position outside of the 60°-sector, the impact is even less severe. The node only does not take part in the contention to forward the packet.

3.4.3 Different Forwarding Strategies & Malicious Nodes

A lot of other forwarding strategies were proposed. For example NFP was introduced in [11] in case of adjustable transmission power. Packets are forwarded to the nearest node with forward progress in order to minimize the overall power consumption and interferences with other transmission (e.g. B in Fig. 1). Basically such other forwarding strategies or any combination of them, restricted to the 60° sector, can be applied as well. The only thing that has to be modified to adapt the algorithm to other forwarding strategies is the delay function in (1) in such a way that, e.g. the node with the least progress introduces also the least delay.

4 Analytical Results†

In the following n and r signify the node density and the transmission range, respectively.

†For a more detailed derivation of all these results see [12].

4.1 Distribution of the Number of Nodes in a 60° Sector

In a first step we assume that the simulation area and the number of nodes are both bounded, where A indicates the number of square kilometers of the simulation area and N the number of nodes $(N_1, \ldots, N_N)$. Each node has a maximal transmission range of r for broadcast transmission. For unicast transmission, we use adjustable transmission ranges up to r as described in section 3.4. The nodes are randomly i.e. independently and uniformly distributed over the whole area. We fix an arbitrary node N_i $(1 \leq i \leq N)$ among these N nodes and an arbitrary direction between 0 and 360° (2π). The direction is chosen uniformly and represents the direction of the destination. The probability that there are k other nodes located in the 60° $(\pi/3)$ sector with radius r in the chosen direction is given through the following binomial distribution. X is a random variable for the number of nodes located within that 60° sector.

$$P(X = k) = \binom{N-1}{k} \left(\frac{r^2\pi}{6A}\right)^k \left(1 - \frac{r^2\pi}{6A}\right)^{N-1-k} \tag{3}$$

This equation actually only holds, if node N_i is located at a minimum distance of r away from any border of the simulation area, i.e. the transmission area of N_i is completely located within the simulation area. But fortunately, this shows up to be irrelevant in a next step. Let N and A go to infinity, but keep the node density n fixed (number of nodes per square kilometer), i.e.,

$$N \to \infty, A \to \infty \quad \text{and} \quad \lim_{N,A \to \infty} \frac{N}{A} = n$$

Further, if we reasonably presume that both, r and n, are in the interval $]0, \infty[$, we obtain from the binomial distribution in (3) a Poisson distribution for the random variable X, only depending on the node density n and the transmission range r.

$$P(X = k) = e^{-n\frac{r^2\pi}{6}} \frac{\left(n\frac{r^2\pi}{6}\right)^k}{k!} \tag{4}$$

From this, we easily obtain the probability p that at least one node is located within the 60° sector with radius r.

$$p = 1 - P(X = 0) = 1 - e^{-n\frac{r^2\pi}{6}} \tag{5}$$

4.2 Expected Number of Hops before Basic Mode Fails

Let Y be a random variable which indicates the number of hops before the algorithms fails in basic mode, i.e. no node is located within the 60° sector towards the destination anymore. 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 $E(Y)$ of the geometrical distribution for the number of successful hops is given by

$$E(Y) = \frac{p}{1-p} = \frac{1-P(X=0)}{P(X=0)} = \frac{1-e^{-n\frac{r^2\pi}{6}}}{e^{-n\frac{r^2\pi}{6}}} \quad (6)$$

4.3 Expected Progress in a Sector

We have to take different aspects into account if we want e.g. to derive the expected progress or the additionally delay per hop. First, if the number of nodes within the 60° sector is larger than 1, only the node with the most progress, i.e. with the minimum introduced additional delay, relays the packet any further (cp. section 3.1). Without loss of generality, we may assume that the transmission range is scaled to 1. Since the 60° ($\frac{\pi}{3}$) sector is symmetrical along the line in the direction of the destination, we may only consider the upper half of the sector (cp. the sector depicted in Fig. 4). In order to be able to calculate, e.g. the average delay per hop introduced by the algorithm, the Poisson distribution of the number of nodes within the sector derived in section 4.1 has to be considered and, as well as the distribution of the progress of the "maximal" node, i.e. of the node with the most progress within that 60° sector. In order to be able to derive this distribution function, we approximate the sector through a triangle with the same area (cp. again Fig. 4).

The density function for the progress of one node located within the triangle is given by

$$f(x) = \begin{cases} \frac{12}{\pi}\frac{1}{\sqrt{3}}x & : \quad 0 \le x \le \sqrt{\frac{\pi}{\sqrt{12}}} \\ 0 & : \quad \text{otherwise} \end{cases}$$

From that we can easily derive the distribution function F_X of X for $0 \le t \le \sqrt{\frac{\pi}{\sqrt{12}}}$.

$$F_X(t) = \int_0^t \frac{12}{\pi}\frac{1}{\sqrt{3}}\, x\, dx = \frac{12}{\pi}\frac{1}{\sqrt{12}}\, t^2 \quad (7)$$

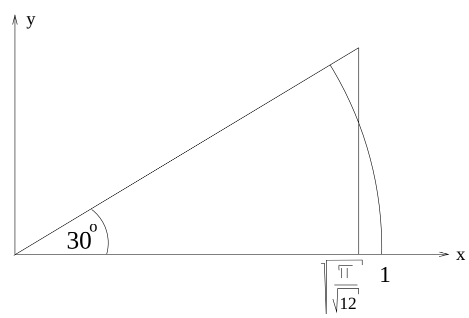

Figure 4: Sector and its approximation by a triangle

Since always only the node with the most progress relays the packet, 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 $(i \le n)$, where the density function of each X_i is given by (7).

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

$$\begin{aligned} F_{max_{i \le n} X_i}(t) &= P(max_{i \le n} X_i \le t) \\ &= P(X_i \le t, \forall i \le n) \end{aligned}$$

$$
\begin{aligned}
&= P(X_1 \le t, \ldots, X_n \le t) \\
&= [P(X_1 \le t)]^n \\
&= [F_{X_1}(t)]^n \qquad (8)
\end{aligned}
$$

Furthermore, it is well known that if for any given random variable Z and its distribution function F_Z, the expected value $E(Z)$ can be calculated in the following way.

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

Together with (7) and (8), we derive the expected progress for a given number of nodes within the triangle.

$$
\begin{aligned}
E(max_{i \le n} X_i) &= \int_0^{\sqrt{\frac{\pi}{\sqrt{12}}}} [1 - (F_X(t))^n]\, dt \\
&= \int_0^{\sqrt{\frac{\pi}{\sqrt{12}}}} \left[1 - \left(\frac{12}{\pi} \frac{1}{\sqrt{12}} t^2\right)^n\right] dt \\
&= \sqrt{\frac{\pi}{\sqrt{12}}}\, \frac{2n}{2n+1} \qquad (9)
\end{aligned}
$$

The reason that the expected progress does not approach asymptotically 1 for $n \to \infty$, but only the constant $\sqrt{\frac{\pi}{\sqrt{12}}} \simeq 0.952$, arises from the fact that we approximate the sector with a triangle of the same area and same angle as shown in Fig. 4. The "length" of the triangle on the x-axis is slightly smaller than of the sector (exactly $\sqrt{\frac{\pi}{\sqrt{12}}}$ times smaller), and therefore the maximal progress of any node is smaller than 1.

4.4 Expected Progress and Delay per Hop

In the previous section solely the expected progress for a given number of nodes located within a sector towards the destination was considered. The actual distribution of the number of nodes within this sector as derived in (4) was not taken into account. To obtain the actual expected progress per hop within a sector of radius 1 (by using its approximation through a triangle), we can derive the following function from (4) and (9) for the expected progress EP depending on the transmission range r and node density n.

$$
\begin{aligned}
EP(n,r) &= \sum_{k=1}^{\infty} e^{-n\frac{r^2\pi}{6}} \frac{\left(n\frac{r^2\pi}{6}\right)^k}{k!} \sqrt{\frac{\pi}{\sqrt{12}}}\, \frac{2k}{2k+1} \\
&= \sqrt{\frac{\pi}{\sqrt{12}}}\, e^{-n\frac{r^2\pi}{6}} \sum_{k=1}^{\infty} \frac{\left(n\frac{r^2\pi}{6}\right)^k}{k!} \frac{2k}{2k+1} \qquad (10)
\end{aligned}
$$

The expected delay per hop proportional to Max_delay can be derived analogoulsy as in (9) and (10).

$$
\begin{aligned}
ED(n,r) &= \left(1-\sqrt{\frac{\pi}{\sqrt{12}}}\right)+ \\
&\quad \sqrt{\frac{\pi}{\sqrt{12}}}\, e^{-n\frac{r^2\pi}{6}} \sum_{k=1}^{\infty} \frac{\left(n\frac{r^2\pi}{6}\right)^k}{k!} \frac{1}{2k+1}
\end{aligned}
$$

The expected delay is basically $1 - EP(n,r)$. The constant $1-\sqrt{\frac{\pi}{\sqrt{12}}} \simeq 0.048$ is due to the way the sector is approximated by a triangle. At least this small delay is introduced per hop, since a node can never have a progress larger than $\sqrt{\frac{\pi}{\sqrt{12}}}$ with our approximation.

5 Simulation Results

In this section some results obtained through a very basic simulator are presented, which are compared to the results obtained analytically in section 4. Basically, nodes are modeled just as points in the plane with no functionality. In order to simulate an unbounded simulation area, only nodes located at a distance larger than the transmission range r away from any border of the area are considered for transmissions (cp. section 4.1). In all the figures, the corresponding analytical function is drawn as well. Rather high node densities are considered in our simulations as well, since if BLR is combined e.g. with TRR [2] such densities may occur along appropriate chosen paths.

5.1 Expected Number of Hops before Basic Mode Fails

We verify the Poisson distribution of (4) by experiments and obtain an exact match between the analytical and simulation results in Fig. 5. We may expect to have several nodes in the 60° sectors with a transmission range of $250\,m$ already for node densities $> 50\,nodes/km^2$. In case of $r = 1000\,m$ already with very low node densities several nodes are located within the sector. The graph corresponding to the derivation in section 4.2 was not compared to any simulation results. But due to the exact match in Fig. 5 we are confident that nevertheless the presented results in Fig. 6 are adequate as well. The expected value of the number of hops until there is no node located in the 60° sector anymore and the basic mode fails is shown on a logarithmic y-axis. For a small transmission range of $100\,m$, we cannot expected that the algorithm works in the basic mode for a large number of hops, since even for high node densities the number of successful hops is relatively low before the fallback mechanism has to be applied. 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.

5.2 Expected Progress in a Sector

In this section simulation results for the expected progress for a given number of nodes within a 60° sector are presented and compared with the analytical result (9) from section 4.3. A transmission range r of 250 meters and a node density of 100 nodes per square kilometer is chosen. (Even though, the results are primarily independent of the parameters.) Furthermore, the expected progress is normalized to a radius of 1.

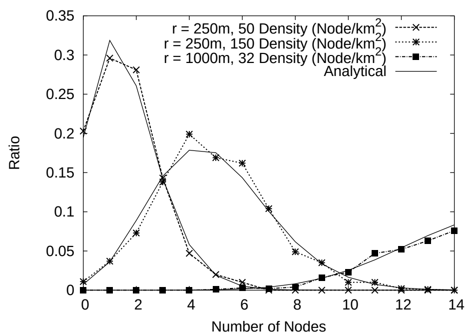

Figure 5: Node distribution

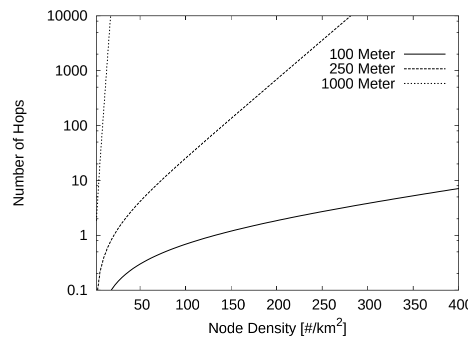

Figure 6: Number of Hops

As expected, the values for the simulation in Fig. 7 are slightly higher than for the analytical curve due to the way the sector is approximated by a triangle (cp. section 4.3). In case there are 3 nodes within the 60° sector, we may already expected that the maximal node of these three has a progress of about 80% of the transmission range r. Even with only one node, the expected progress is almost $\frac{2}{3}r$. The dotted line indicates the maximal achievable progress in the triangle $\sqrt{\frac{\pi}{\sqrt{12}}}$. The values of the simulation can actually be higher since packets can be forwarded to nodes within the sector and not the triangle. (cp. the peak at a node density of 11).

5.3 Expected Progress per Hop

In Fig. 8 the expected progress per hop for a certain node density n and transmission range r is depicted (cp. section 4.4). Again the values are normalized to a radius of 1.

For a transmission range over 250 meters, the expected progress per hop increases steeply at the beginning and quickly approaches the maximal transmission range. Therefore, the results indicate that the energy wasted because a node has to transmit some packets at full power, and not at the optimal power level due to the lack of position information about its neighbors, is negligible even for sparse networks. The graph for the expected delay $ED(n, r)$ introduced per hop is not depicted. But due to the simple correlation of $ED(n, r) \simeq 1 - EP(n, r)$, we may conclude that for $r = 250\,m$ already with a density of 100 nodes per

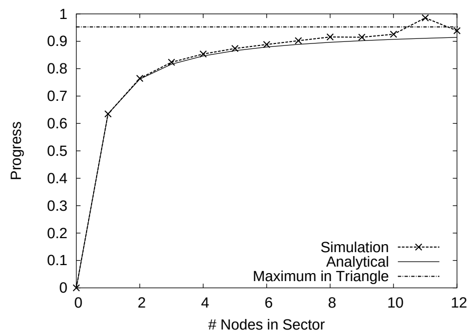

Figure 7: Expected progress

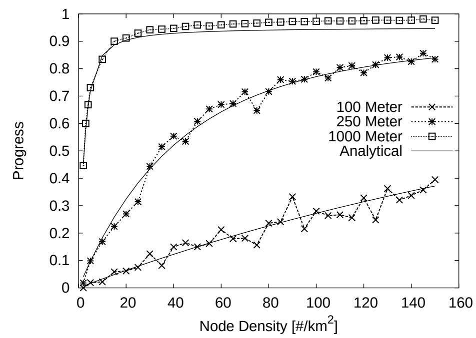

Figure 8: Expected progress per hop

square kilometer, the additional delay is only about 20% of the maximum delay. For larger transmission ranges, even shorter delays are obtained for much lower node density. Since for large transmission ranges the maximal performance in terms of progress and delay per hop is already achieved with very low node densities, nodes may operate a great part of the time in sleep mode in dense network without degrading the overall performance significantly. For example with $r = 1000$, the progress per hop is almost the same for node densities of 10 and 100. Therefore 90% of the nodes may be in sleep mode with almost no negative effect.

6 Conclusion

In this paper a novel position-based routing algorithm BLR for mobile ad-hoc networks is described which avoids any beaconing mechanisms. Since beaconing mechanisms are costly and nodes are battery-powered, it is especially important to avoid any unnecessary transmission, reception, and processing of packets. BLR only requires nodes to be aware of their own position and the position of the upstream and destination nodes upon the reception of a packet. Solely this location information is used at each node in order to determine in a completely distributed way a node which forwards the packet further by introducing a small additional delay depending on the relative position to the destination location and previous node.

The behavior of the BLR algorithm in basic mode was evaluated by analytical means and the obtained results were verified through simulations. Transmission ranges larger than 200 meters are required for the algorithm to work in basic mode most of the time and thus to perform best; unless we have rather high node densities. The algorithm continues to work if it fails in basic mode, but additional delay is introduced and some transmissions are evoked in backup mode to recover from this failure. Nevertheless, BLR is able to provide efficient and battery-conserving routing in mobile ad-hoc networks.

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