HELSINKI UNIVERSITY OF TECHNOLOGY

Local Forwarding Methods in Large Ad Hoc Networks

Jarno Nousiainen
21.8.2007

Contents

1 Introduction

This study presents three new local forwarding methods for geographic routing in large ad hoc networks. Their performance is studied via simulations, and the results are compared with those of other forwarding methods from the literature.

1.1 Ad hoc networks

The earliest applications of packet radio networks, as they were called back then, were mainly for military purposes and have been studied since the 1970s. The appearance of inexpensive WLAN solutions during the 1990s made ad hoc networks a popular research topic, and the increasing availability of wireless devices ever since has made ad hoc networking one of today's most active fields in communications research.

The term ad hoc network itself refers to a computer network with no fixed infrastructure where the nodes usually communicate in a wireless fashion. The decentralization of the network means that nodes are responsible for all network activity, which includes discovering the route to the destination and forwarding packets towards it. Since topology changes due to node mobility are also possible, the connections can only be established for the duration of the communication session.

The performance of an ad hoc network can be measured using indicators such as throughput, latency, energy consumption, and fairness, and it is closely related to the concepts of routing and medium access control (MAC). Routing is responsible for providing the paths for the traffic, while MAC provides addressing and channel access control mechanisms. For the performance to be as good as possible, routing and MAC have to be usually designed to work together.

1.2 Objective of the study

This study examines dense ad hoc networks where a typical path between a sender and a receiver consists of a large number of hops, see [1] and [2]. In such a setting, the packet forwarding at the microscopic level works on the scale of an individual node and its neighbors. At this level, the task is to maximize the packet flow in the given direction.

The average progress of a packet per timeslot for an arbitrary node, D, used to describe the performance of a forwarding method, depends on the transmission probability, the probability of successful reception, and the average progress of the packet in the given direction, i.e.,

$$D = \mathbb{P}(\text{node transmits})\cdot\mathbb{P}(\text{no collisions})\cdot\mathbb{E}[\text{progress of a packet} \mid \text{successful transmission}].$$

The question of interest in this study is whether it is possible to improve the performance of local forwarding combined with slotted ALOHA type MAC by taking the receiver's number of neighbors into account. The idea is to forward traffic to sparser areas of the network, thus increasing the probability of successful reception as the average number of competing transmissions is lower.

Another area of interest is the possibility of using real-time information about the number of receiver's active neighbors. When the actual number of each possible receiver's active neighbors is known, we are able to calculate and maximize the true expected progress of the packet during the current time slot.

2 Routing in ad hoc networks

2.1 Traditional routing methods

For communication within the network to be possible, a routing protocol is required to establish a connection between the participating nodes. Because an ad hoc network does not have a fixed infrastructure or centralized control, the nodes are responsible for performing the routing functions themselves.

The special nature of large ad hoc networks places some requirements on the routing protocol. Movement of the nodes causes changes to the network topology and the routing protocols need to be able to adapt to these changes. At the same time the routing overhead should be kept minimal since the bandwidth in the shared wireless channel is limited. Efficient use of the channel is crucial also to save battery power, which is an issue with mobile devices.

Traditional ad hoc routing protocols fall into two general categories: proactive (table driven) and reactive (on-demand). Proactive routing protocols maintain information about the whole network in every single node. With a complete picture of the network, determining a route is fast, but whenever the topology changes, all the routing tables need to be updated. This means that recurrent changes in the topology, especially in case of a large network, cause the amount of overhead traffic to increase significantly. Hence, proactive routing protocols, including Destination-Sequenced Distance Vector (DSDV [3]), Fish-eye State Routing (FSR [4]), and Optimized Link State Routing (OLSR [5]), perform best when the nodes have low mobility compared to the frequency with which they transmit data.

Reactive routing protocols do not maintain routing tables about the whole network. Instead, a route is only found when there is data to send. This reduces the amount of routing traffic caused by the changes in the network topology and also the storage capacity needed. Whenever the information about the required route is not available, a node starts a route discovery procedure, causing a significant delay before the packet can be transmitted. Thus, reactive ad hoc routing protocols, including Dynamic Source Routing (DSR [6]), Ad Hoc On-Demand Distance Vector (AODV [7]), and Temporally Ordered Routing Algorithm (TORA [8]), are most useful when the network topology changes constantly or when data transmissions are infrequent and delay tolerant.

There exist also hybrid protocols that combine both proactive and reactive routing protocols. Since proactive and reactive routing schemes work well in opposite types of networks, it is possible to utilize them hierarchically to increase the performance compared to the pure proactive and reactive protocols. Examples of hybrid protocols include Zone Routing Protocol (ZRP [9]) and AntHocNet [10].

2.2 Geographic routing

Traditional routing protocols presented above collect and store information about the network topology, and it is questionable whether this kind of approach is feasible when the number of nodes reaches hundreds or thousands. Geographic routing protocols (see [11] for an overview) are a promising alternative for large ad hoc networks, and they use the geographic locations of the nodes as a base for their routing decisions. If the location of the destination is known, a node needs only local information about its own and its neighbors' locations to be able to forward the packet. Hence, the scalability of such protocols is mostly dependent on the location service which performs the tracking of the destination nodes.

The most obvious way of making the decision about the next hop is to try to forward the packet as far as possible with respect to a given progress metric. These greedy forwarding methods include, for example, Most Forward within Radius (MFR [12]) and Geographical Distance Routing (GEDIR [13]). However, to work properly a geographic routing protocol needs to be able to handle routing around concave nodes, i.e., nodes that have no neighbors in the direction of the destination (forward neighbors). Typically routing algorithms that guarantee packet delivery work as follows: greedy forwarding is used as long as possible, but when packet reaches a dead end, a recovery procedure such as face routing [14] is taken into practice. Geographic routing protocols using face routing include Greedy Face Greedy (GFG [14]), Greedy Other Adaptive Face Routing (GOAFR [15]), and Greedy Perimeter Stateless Routing (GPSR [16]).

When an ad hoc network consists of a very large amount of nodes, the source and the destination of a packet are usually far from each other, and typical routes consist of many hops. In this kind of scenario, it is possible to analyze the network at a macroscopic and microscopic level [1]. The approach is similar to the one in Trajectory Based Forwarding (TBF [17]). At the macroscopic level, the network can be seen as a continuous medium through which the packets are routed along smooth geometric curves. The task is to achieve optimal load balancing, thus providing the direction of the packet flow to the microscopic level. The microscopic level works on the scale of an individual node and its neighbors. The task of the microscopic level is to maximize the packet flow in the given direction.

3 Network model

3.1 Assumptions

A large ad hoc network similar to the one in [2] is considered. When the overall number of nodes in the network is large, two randomly selected nodes are, on the average, much further apart from each other than two neighboring nodes. Thus, a route between a source and a destination typically consists of a large number of hops and the nodes are mostly relaying traffic. Therefore only relay traffic is considered and no originating or terminating traffic exists in the model.

Because packets moving in opposite directions are more likely to cause collisions than traffic flowing in certain direction, it makes sense to handle different directions by appropriate scheduling based on time sharing. As a result, it is enough to consider traffic flowing in one, given, direction. Node mobility or failures are not considered, but network is assumed to be static, and the nodes to be located according to the spatial Poisson point process in two dimensions. The intensity of the process, referred to as the node density, is denoted by λ [1/m^2].

Each node has an omni-directional antenna, i.e., signals can be received from and transmitted to all directions, and the same transmission power, resulting in a common fixed transmission radius R [m]. All nodes are assumed to have the same transmission frequency meaning that a node is able to hear all the transmissions from nodes within its communication range and none from those outside. A simple Boolean interference model is used to model the collisions in the network. If a node hears more than one transmission within its transmission range (including its own), it is not able to receive any of them. A node is only able to successfully receive a packet if there is exactly one transmission within the area defined by the radius R.

Additionally, the use of slotted ALOHA [18] type MAC protocol is assumed. This means that the system is synchronous, and time is divided into slots. The packet size is fixed for the transmission time to match the length of a time slot. As the transmissions can only start at the beginning of a time slot, packets overlap either completely or not at all. The protocol is characterized by a single parameter p which defines the probability that a node with queued packets transmits in a given time slot. It is also assumed that successful transmissions are acknowledged, and the size of such acknowledgement packet is small compared to the size of a data packet which dominates the time slot duration. The parameter p is constant, which means that no backoff scheme is applied in retransmissions.

Finally, it is assumed that a node has the necessary information to be able to make the forwarding decision locally according to the rules in question. This means that a node knows, in addition to its own coordinates, the coordinates of its neighbors and the direction of the packet flow. Furthermore, a node knows the number of neighbors of each of its own neighbors and possibly how many of them are actually active, i.e., have packets to send. No cost has been placed to the additional information and it is assumed that it can be exchanged, e.g., with regular control or acknowledgement messages.

3.2 Mean density of progress

The performance of a forwarding method from a single node's point of view can be defined as the average progress of a packet in a given direction per timeslot [12]. This mean progress, D [m], is given by

$$\begin{aligned} D(N_R, p) &= \mathbb{P}(\text{node transmits}) \cdot \mathbb{P}(\text{no collisions}) \\ &\quad \cdot \mathbb{E}[\text{progress of a packet} \mid \text{successful transmission}], \end{aligned} \tag{3.1}$$

and under the assumptions it depends only on the average number of nodes within the transmission range, $N_R = \lambda \pi R^2$, and the transmission probability p.

The mean number of nodes in a differential area element equals $\lambda \cdot dA$. Thus, a network level measure for the performance, the average progress of packets per unit time per unit area or the mean density of progress, I $[1/(\mathrm{m} \cdot \mathrm{s})]$, can be expressed as

$$I(N_R, p) = \frac{\lambda \cdot dA \cdot D(N_R, p)}{dA \cdot \Delta t} = \frac{\sqrt{\lambda}}{\Delta t} \cdot u(N_R, p), \tag{3.2}$$

where Δt denotes the duration of a time slot $[s]$ and $u = \sqrt{\lambda} \cdot D$ is the dimensionless mean progress of a packet. The dimensionless mean progress u is used instead of D to reduce the number of physical parameters. The convenience of $1/\sqrt{\lambda}$ as the unit length related to the model is based on the fact that the average distance between two nearest terminals is $1/(2\sqrt{\lambda})$ [12], but as well as $1/\sqrt{\lambda}$, the transmission radius R could have been used.

4 Simulation model

Some analytical results on local performance under heavy traffic are available (for example see [12]), but they fail to model the impact of bottlenecks in the network caused by forwarding. Because analytical results are hard to achieve, the dimensionless mean progress of a packet (per time slot per node), $u(N_R, p)$, is maximized via simulations.

For the results to be comparable, a simulation model similar to [2] is used. To keep the simulation times feasible a unit square with an average of thousand nodes ($\lambda = 1000$) is chosen to represent the supposedly infinite network. The harmful border effects are avoided by connecting the opposite sides of the square together to form a torus. Since recovering from concave nodes would require some specific procedure as stated in Section 2.2, all such nodes are recursively removed from the network until there are none. This is equal to a rule that forbids nodes from sending packets to concave neighbors (or neighbors with only concave neighbors, etc.) Furthermore, in the dense networks ($N_R > 10$) we are studying, the amount of concave nodes is very small ($\mathbb{P}(\text{node concave}) = e^{-\frac{1}{2}N_R}$).

The assumption about relay traffic is fulfilled by placing packets with infinite lifetime to the network. No new packets are generated during the simulation and the existing packets circle around the torus for as long as the simulation lasts. Because the goal is to find the greatest sustainable mean density of progress, the network is simulated under saturated traffic. Hence, the initial number of packets placed in each node ($M = 50$) is experimentally chosen such that a further increase would have no significant effect on $u(N_R, p)$.

When the simulation parameters λ and Δt are fixed, the task of maximizing $I(N_R, p)$ equals maximizing $u(N_R, p)$ with respect to N_R and p. During the simulation the total distance traveled by each packet is monitored, thus allowing the estimation of $D(N_R, p)$ with the equation

$$D(N_R, p) = \frac{1}{TN} \sum_{i=1}^{NM} S_i, \tag{4.1}$$

where T is the simulation time [time slots], N is the number of nodes and S_i is the distance traveled by the packet i. The estimate for $u(N_R, p)$ is achieved simply by multiplying D by $\sqrt{\lambda}$.

5 Forwarding methods

5.1 Reference methods

Probably the most obvious way to forward packets locally is to maximize the possible progress in the given direction. Such a method is the first proposed geographic forwarding method Most forward within radius, MFR. It is a simple greedy method which chooses the neighbor j with the greatest distance d_{ij} from the sender i measured in the direction of the packet flow, that is,

$$j = \arg\max \ d_{ij}. \tag{5.1}$$

In static networks the use of MFR leads to poor utilization of the network. Only a small fraction of the nodes is active as the traffic is concentrated on certain paths [2].

The easiest way to spread traffic is to select the receiver completely randomly. In Random forwarding (RF) all the forward neighbors have equal probability q_{ij} of becoming the next hop, i.e., each neighbor in the direction of the packet flow is assigned with probability

$$q_{ij} = \frac{1}{N_{F_i}}, \tag{5.2}$$

where N_{F_i} is the number of forward neighbors of sender node i.

In Weighted random forwarding (WRF) the probabilities are proportional to the locations of the forward neighbors. The idea is to increase the average hop length compared to Random forwarding. The probability assigned to forward neighbor j is

$$q_{ij} = \frac{d_{ij}}{\sum_{k=1}^{N_{F_i}} d_{ik}}. \tag{5.3}$$

Opportunistic forwarding (OF) demonstrates the benefits of local coordination. In OF a packet is broadcasted to all forward neighbors, and from the forward neighbors that were able to receive the packet, the one with the greatest progress d_{ij} is chosen afterwards with a specific local coordination mechanism (cannot be achieved with slotted ALOHA). Thus, the receiving node

$$j = \arg\max \ d_{ij} \mathbb{1}_{R_j}, \tag{5.4}$$

where $\mathbb{1}_{R_j} = 1$ if neighbor j receives the transmission, i.e., there is no collision, and zero otherwise. The idea for OF comes from the ExOR protocol [19], but it has been modified mainly to avoid duplicate packets.

5.2 Modified weighted random forwarding

The first of the new forwarding methods (WRFm1) is a slightly modified version of the WRF method. The probabilities assigned to each forward neighbor are proportional to the distance traveled in the given direction per the number of neighbors the neighbor j has. The probability q_{ij} that sending node i chooses node j as the receiver is

$$q_{ij} = \frac{d_{ij}/N_{R_j}}{\sum_{k=1}^{N_{F_i}} d_{ik}/N_{R_k}}, \tag{5.5}$$

where N_{R_j} is the number of neighbors of node j. Since the actual changes in the weights are relatively small compared to WRF the method should give some idea whether it is beneficial to favor nodes with fewer neighbors.

5.3 Weighted expectation forwarding

In WEF the weights are proportional to the expected progress under heavy traffic assumption. If it is assumed that all the nodes have packets to send, the expected progress of a packet that is being sent can be calculated. In this method the nodes with fewer neighbors get significantly higher probabilities than the ones with several neighbors. The probabilities are calculated with the equation

$$q_{ij} = \frac{d_{ij}(1-p)^{N_{R_j}}}{\sum_{k=1}^{N_{F_i}} d_{ik}(1-p)^{N_{R_k}}}. \tag{5.6}$$

5.4 Current maximum expectation forwarding

In CMEF additional information about the activity and the number of active neighbors of node j is assumed. When the actual number of neighbor's neighbors that can possibly send during the current time slot is known, it is possible to calculate, and thus maximize the true expected progress of the packet. Because the amount of queued packets in each node changes during the simulation, the method is not deterministic and is thus hopefully able to avoid the problems associated with the MFR method. Consequently the next hop j is chosen to be

$$j = \arg\max d_{ij}(1-p)^{N_{A_j}-1+\mathbb{1}_{A_j}}, \tag{5.7}$$

where N_{A_j} is the number of active neighbors, i.e., neighbors with queued packets, of node j and $\mathbb{1}_{A_j} = 1$ if node j has queued packets and is zero otherwise.

6 Results

6.1 Dimensionless mean progress

Figures 6.1, 6.3, and 6.4 show the dimensionless mean progress of a packet, $u(N_R, p)$, as a function of p for each of the forwarding methods with several values of N_R. Based on the left subfigures, more simulations were made to determine more precise values for the optimums. The results of these simulations are depicted in the right subfigures with the corresponding 90% confidence intervals. All the forwarding methods and parameter combinations were simulated over the same set of network realizations. This reduces the variance between the points in the figures, and though the confidence intervals are correct for a single point, the probability that the true value of one parameter combination is at the upper end of the interval, and the true value of another is at the lower end, is thus smaller. The maximum values of the dimensionless mean progress for each new forwarding method are represented in Table 6.1 with the corresponding values of N_R and p.

Table 6.1: The maximum $u(N_R, p)$ for each new forwarding method and the corresponding N_R and p.

	$u(N_R, p)$	N_R	p
WEF	0.02532	16.5	0.2125
WRFm1	0.02971	13.5	0.3375
CMEF	0.04672	13.5	0.4250

As shown in Table 6.1, WEF produced the worst results. This is due to the fact that the idea behind the method was to calculate the expected progress for each neighbor under heavy traffic, and use them as weights. In reality only about 20% of the nodes are actually active in the steady state of the network. As a result, too much emphasis was given to the receiver's number of neighbors.

As can be seen from Figure 6.2, the amount of empty nodes increases fast in the beginning

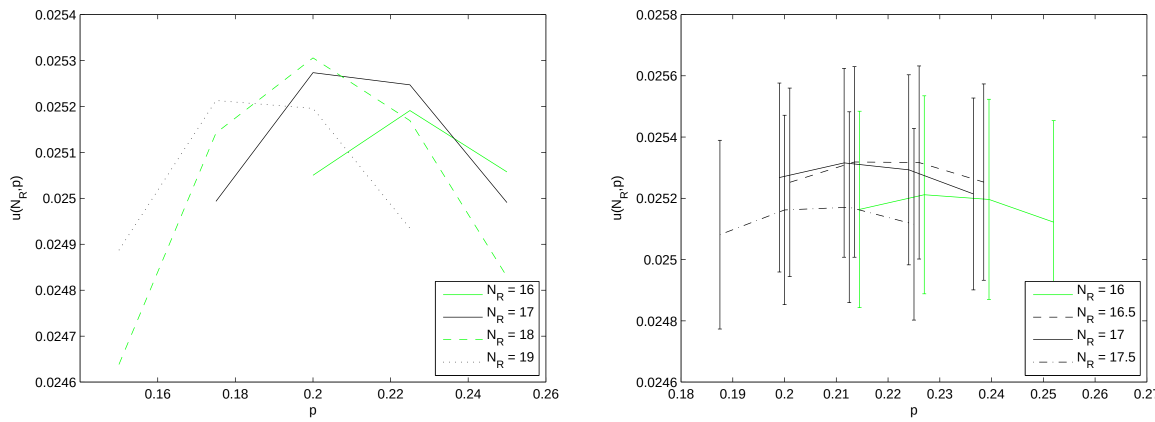

Figure 6.1: The dimensionless mean progress of a packet, $u(N_R, p)$, as a function of p for WEF. The left subfigure presents the averages over 125 network realizations, and the right over 250 network realizations with the corresponding 90% confidence intervals as error bars.

of the initial transient when using WEF. This shows that WEF seems to be efficient (it actually outperforms the WRF methods) when the heavy traffic assumption applies. But when the number of idle nodes increases, the correlation coefficient between the number of neighbors and the probability of successful transmission (or their logarithms) decreases, resulting in a more random method than would be beneficial in terms of performance. The randomness of the method also came up in simulations where twice the amount of realizations was needed to produce approximately the same kind of convergence as in other methods.

The Modified weighted random forwarding method gave less weight on the receiver's number of neighbors than WEF and was able to outperform it by over 15%.

As expected, Current maximum expectation forwarding which had access to the information about the precise number of neighbors that could possibly transmit during the time slot for each possible receiver performed the best of the three methods. CMEF was able to achieve ca. 50% higher $u(N_R, p)$ compared to Modified WRF. The difference is largely due to the ability to avoid collisions. This can also be seen when the initial transient duration is studied. During the initial transient when the traffic is spread more evenly among nodes, methods that do not take the current traffic situation into account have a high number of colliding transmissions. Hence, it takes longer before the nodes that are

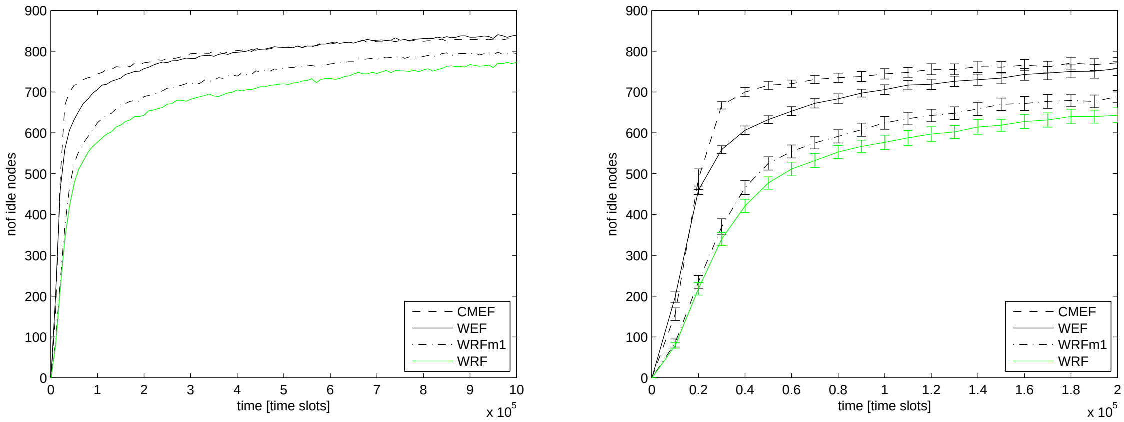

Figure 6.2: The number of idle nodes during the initial transient of $8 \cdot 10^5$ time slots for CMEF, WEF, Modified WRF, and WRF. The right subfigure shows the values for the beginning of the simulation with corresponding 90% confidence intervals. The values are averages over 25 network realizations.

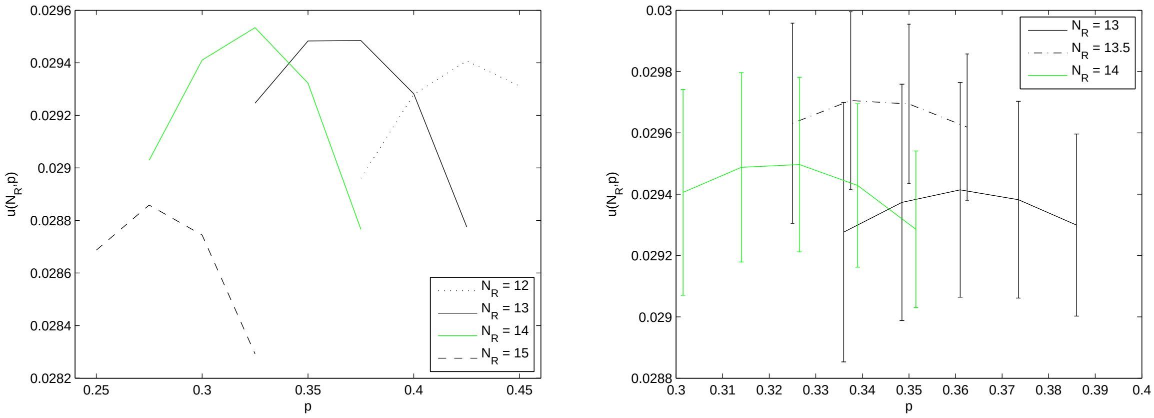

Figure 6.3: The dimensionless mean progress of a packet, $u(N_R, p)$, as a function of p for Modified WRF. The left subfigure presents the averages over 50 network realizations, and the right over 125 network realizations with the corresponding 90% confidence intervals as error bars.

outside the main paths of the traffic, and do not usually have packets to forward during the steady state, have their initial queues emptied. CMEF is able to avoid collisions, and the amount of idle nodes increases much faster that with the WRF methods as can be seen from Figure 6.2.

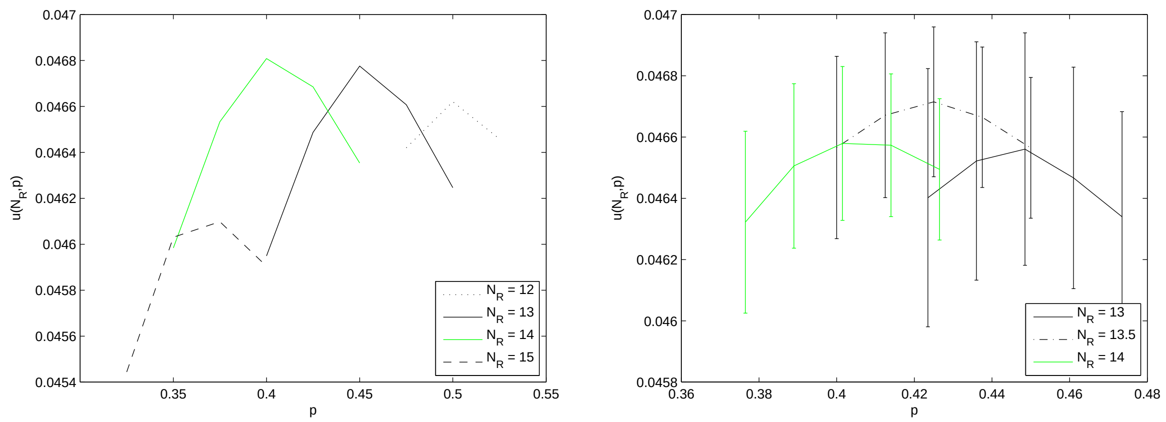

Figure 6.4: The dimensionless mean progress of a packet, $u(N_R, p)$, as a function of p for CMEF. The left subfigure presents the averages over 50 network realizations, and the right over 125 network realizations with the corresponding 90% confidence intervals as error bars.

6.2 Comparison

The maximum values of the dimensionless mean progress of a packet for the new as well as the reference methods [2] are listed in Table 6.2.

It can be easily seen that deterministic forwarding (MFR) is not suitable for the used network setup, and the performance can be doubled by switching to a method that spreads the traffic better. WEF loses to WRF, but is still able to outperform completely random forwarding (RF).

The optimal values of N_R and p for WEF differ from the values of the other methods with a similar working principle. A smaller transmission probability, p, gives less weight to the number of neighbors which, as discussed, loses some of its relevance in the steady state. A smaller p also allows a greater N_R, which reduces the relative standard deviation of the number of active neighbors. The WRF methods have a higher p than RF since the number of empty nodes increases when some nodes are assigned with lower probabilities and thus receive packets only rarely.

The mean progress achieved with the Modified WRF was about 5% larger than with the original WRF. Additional simulations (see Figure 6.5 for comparison) showed that the difference is statistically significant with a p-value of $3.2 \cdot 10^{-18}$. It is also to be

Table 6.2: The maximum $u(N_R, p)$ for each forwarding method along with the corresponding N_R and p.
* The number of neighbors for each receiver is known.
† The number of active neighbors, i.e., ones with queued packets for each receiver is known.
‡ The receiver with the best achieved progress is chosen after sending the packet to all receivers.

	$u(N_R, p)$	N_R	p
MFR	0.0126	50	0.35
RF	0.0222	14	0.25
WEF*	0.0253	16.5	0.21
WRF	0.0279	14	0.30
WRFm1*	0.0297	13.5	0.34
CMEF†	0.0467	13.5	0.43
OF‡	0.0590	18	0.40

noted that when the traffic was more evenly spread among the nodes than in the steady state simulations, the difference between the two forwarding methods seemed to be even greater.

Though CMEF was able to outperform other methods by a clear margin, the difference between the best expectation (CMEF) and the best realization (Opportunistic forwarding, OF) was still over 25%. The performances are not directly comparable, since while CMEF needs information about the current status of the network before making the forwarding decision, OF uses specific control mechanism to select the receiver with the greatest progress afterwards. Because all the forward neighbors can receive the packet instead of just one, OF is able to efficiently avoid collisions, which leads to better performance and explains higher optimal values for N_R and p.

The analytical results of [12] give the optimal values of $u^*(N_R, p) = 0.0431$, $N_R^* = 7.72$, and $p^* = 0.113$ for MFR under heavy traffic assumption. The idle nodes in the simulations reduce the average transmission frequency of a node causing the mean progress of a packet to decrease as well. Because of the idle nodes, the average number of neighbors, N_R, and/or the transmission probability, p, can also be higher.

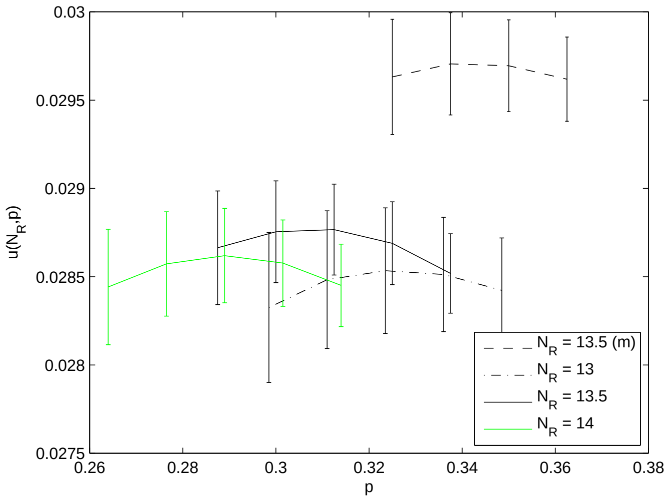

Figure 6.5: The dimensionless mean progress of a packet, $u(N_R, p)$, as a function of p for WRF and Modified WRF. The simulated optimum values for WRF were $u^* = 0.0288$, $N_R^* = 13.5$, and $p^* = 0.31$. The difference between the dimensionless mean progresses of the methods is statistically significant.

7 Conclusion

In geographic routing of large, dense ad hoc networks, it is possible to present a problem decomposition where on the macroscopic level the task is to balance the traffic load on paths forming smooth geometric curves, and on the microscopic level to maximize the packet flow in a direction given from the macroscopic level.

In this paper, three new forwarding methods for geographic routing were presented to be simulated in a model with a minimal set of parameters under the assumption of a slotted ALOHA type MAC protocol. These new local forwarding methods were based on the idea of avoiding collisions by directing traffic to sparser areas of the network where competing transmissions should be rarer. This was done by taking the receiver's number of neighbors into account when making the routing decision. Also a situation where the actual number of active neighbors was assumed to be known was taken under consideration.

The results showed that it is possible to increase the performance, i.e., the mean density of progress, if the number of neighbors of each receiver is known. In steady state simulations, though, the difference between the modified and the original WRF was not that appreciable, but if the traffic load was more evenly spread, the benefit from avoiding the collisions seemed to grow. On the other hand, if the information about whether a node actually has packets to send was known for each neighbor (and their neighbors), it was possible to achieve a significantly higher mean density of progress.

Opportunistic forwarding provided a practical upper limit for performance that is achievable with local coordination. Simple forwarding methods based on random forwarding fell far from this limit, while the method maximizing the true expected progress (CMEF) performed about 20% worse. One possibility of trying to still close the gap would be to monitor the actual queue lengths, although a more interesting topic could be the actual maximum performance of the network achievable with (global) coordination.

References

[1] E. Hyytiä and J. Virtamo. On load balancing in a dense wireless multihop network. In *NGI 2006, 2nd Conference on Next Generation Internet Design and Engineering*, pages 72–79, València, Spain, 2006.

[2] O. Apilo, P. Lassila, and J. Virtamo. Performance of local forwarding methods for geographic routing in large ad hoc networks. In *Proc. of The Fifth Annual Mediterranean Ad Hoc Networking Workshop (Med-Hoc-Net 2006)*, Lipari, Italy, 2006.

[3] Charles E. Perkins and Pravin Bhagwat. Highly dynamic destination-sequenced distance-vector routing (DSDV) for mobile computers. In *Proc. of ACM SIGCOMM'94 Conference on Communications Architectures, Protocols and Applications*, pages 234 – 244, London, UK, August – September 1994.

[4] Guangyu Pei, Mario Gerla, and Tsu-Wei Chen. Fisheye state routing: A routing scheme for ad hoc wireless networks. In *Proc. of IEEE International Conference on Communications*, pages 70 – 74, New Orleans, Lousiana, June 2000.

[5] P. Jacquet, P. Mühlethaler, T. Clausen, A. Laouiti, A. Qayyum, and L. Viennot. Optimized link state routing protocol for ad hoc networks. In *Proc. of IEEE Inter-*

national Multi Topic Conference INMIC, pages 62 – 68, Lahore, Pakistan, December 2001.

[6] David B. Johnson and David A. Malz. Dynamic source routing in ad hoc wireless networks. In Tomasz Imielinski and Henry F. Korth, editors, *Mobile Computing*, volume 353 of *The Kluwer International Series in Engineering and Computer Science*. Kluwer Academic Publishers, 1996.

[7] Charles E. Perkins and Elizabeth M. Royer. Ad-hoc on-demand distance vector routing. In *Proc. of IEEE Workshop on Mobile Computing Systems and Applications*, pages 90 – 100, New Orleans, Lousiana, February 1999.

[8] Vincent D. Park and M. Scott Corson. A highly adaptive distributed routing algorithm for mobile wireless networks. In *Proc. of IEEE INFOCOM*, pages 1405 – 1413, Kobe, Japan, April 1997.

[9] Zygmunt J. Haas. A new routing protocol for the reconfigurable wireless networks. In *Proc. of IEEE International Conference on Universal Personal Communications*, pages 562 – 566, San Diego, California, October 1997.

[10] Frederick Ducatelle, Gianni Di Caro, and Luca Maria Gambardella. Using ant agents to combine reactive and proactive strategies for routing in mobile ad hoc networks. *International Journal of Computational Intelligence and Applications*, 5(2):169 – 184, 2005.

[11] Ivan Stojmenovic. Position-based routing in ad hoc networks. *IEEE Communications Magazine*, 40(7):128–134, 2002.

[12] Hideaki Takagi and Leonard Kleinrock. Optimal transmission ranges for randomly distributed packet radio terminals. *IEEE Transactions on Communications*, 32(3):246–257, 1984.

[13] Ivan Stojmenovic and Xu Lin. Loop-free hybrid single-path/flooding routing algorithms with guaranteed delivery for wireless networks. *IEEE Transactions on Parallel and Distributed Systems*, 12(10):1023–1032, 2001.

[14] Prosenjit Bose, Pat Morin, Ivan Stojmenović, and Jorge Urrutia. Routing with guaranteed delivery in ad hoc wireless networks. *Wireless Networks*, 7(6):609 – 616, 2001.

[15] Fabian Kuhn, Roger Wattenhofer, and Aaron Zollinger. Worst-case optimal and average-case efficient geometric ad-hoc routing. In *Proc. of International Conference on Mobile Computing and Networking*, pages 267 – 278, Annapolis, Maryland, June 2003.

[16] Brad Karp and H.T. Kung. GPSR: Greedy perimeter stateless routing for wireless networks. In *Proc. of International Conference on Mobile Computing and Networking*, pages 243 – 254, Boston, Massachusetts, August 2000.

[17] Dragoş Niculescu and Badri Nath. Trajectory based forwarding and its applications. In *Proc. of International Conference on Mobile Computing and Networking*, pages 260 – 272, San Diego, California, September 2003.

[18] Lawrence G. Roberts. Aloha packet system with and without slots and capture. Technical Report ARPA Satellite System Note 8, Stanford Research Institute, Stanford, California, June 1972.

[19] Sanjit Biswas and Robert Morris. Opportunistic routing in multi-hop wireless networks. In *Proc. of ACM Second Workshop on Hot Topics in Networks*, Cambridge, Massachusetts, November 2003.