Performance of Local Forwarding Methods for Geographic Routing in Large Ad Hoc Networks

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***Abstract*— We consider local geographic forwarding methods in a network of stationary wireless nodes. The task of the local forwarding is to select the next-hop for each packet so as to maximize the flow of packets in a given direction. According to our network model with a slotted ALOHA type MAC protocol, the flow of packets, as expressed by the mean density of progress, depends on a minimal number of MAC layer parameters, namely the transmission range (or power) and the probability to transmit in a time slot. Our aim is to evaluate the maximum mean density of progress with respect to these two parameters for four different forwarding methods, distinguished by the next hop selection rules, and to compare their performance. Our results show that deterministic forwarding (MFR) suffers from concentration of the traffic onto certain deterministic paths. The two randomized methods are able to spread the traffic more efficiently and achieve a better performance. However, considerably better results are obtained with an opportunistic method, where the MAC layer is enhanced with functionality to choose the best available receiver, demonstrating the benefits of using local coordination.**

***Index Terms*— ad hoc networks, geographic routing, MFR, randomized forwarding, density of progress**

I. Introduction

Traditional ad hoc routing protocols have been classified into proactive and reactive methods. However, both approaches often fail to scale well in large ad hoc networks. Significantly better scalability can be achieved if geographic location information is readily available leading to a class of routing methods known as geographic routing [1]. Availability of geographic location information renders the routing decision simple and requiring only local information. The next-hop decision rules determine the *local forwarding method*. Greedy methods try to forward the packet as "far as possible" according to a given progress metric. An early approach to geographic forwarding is the so called Most Forward within Radius (MFR) [2], which uses as its metric the progress made in a given direction. On the other hand, GEDIR [3] uses pure Euclidean distance as the metric. Compass routing [4] tries to minimize the divergence of the forwarding with respect to the given direction. A generalized cost metric taking into account, e.g., packet error rates or delays, has been proposed in [5].

However, a particular property of geographic routing is that there exist so called concave nodes, i.e., nodes that do not have any forward neighbors according to the used progress metric in a given direction. A complete geographic routing protocol also needs to handle routing around concave nodes. GFG [6] is a recent approach and utilizes so called face routing, which is a stateless method that guarantees the existence of a loop-free path to the destination. The general idea is to use greedy forwarding as long as possible, use face routing as a recovery method to deal with a concave node, and switch back to greedy forwarding as soon as a node is reached that is closer to the destination than the concave node. The drawback of face routing is that the routes generated by the method may be very long. However, this problem can also be improved by limiting the region how much face routing is allowed to diverge from the destination, as is done in GOAFR+ [7]. A promising new approach is to combine geographic forwarding with a locally coordinated MAC scheme [8].

We analyze the performance of geographic forwarding methods in a particular setting that allows a systematic evaluation of the performance under a minimal set of system parameters. To achieve this we consider an ad hoc network with a large number of nodes, and correspondingly also the routes consist of a large number

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of hops. In this setting, the routing problem with the objective of maximizing the total amount of traffic the network can carry under a given traffic pattern can be divided into two separate problems, those at macroscopic and microscopic levels, see [9]. A similar approach, Trajectory Based Forwarding, for large ad hoc networks has also been proposed in [10]. At the macroscopic level the task is to achieve optimal load balancing by choosing the routes (considered as smooth geometric curves) such that the maximum traffic intensity over the network is minimized. At the microscopic level the task is to define a local forwarding method for next-hop selection that maximizes the flow of packets in a given direction.

We focus on the latter problem and the aim is to compare the performance of alternative forwarding methods. In our network model, for simplicity, we assume the so called Boolean interference model with all nodes having the same constant transmission range (power) and a slotted ALOHA type MAC protocol, which is characterized by a single parameter, i.e., the probability to transmit in a time slot. The performance is expressed as the mean density of progress (mean packet flow). We take the node density of the network, i.e., the mean number of nodes per unit area, to be a given parameter. Then the mean density of progress in a given direction only depends on a minimal number of MAC layer parameters, namely the slotted ALOHA parameter and the transmission range of a node. Our aim is to find the maximum mean density of progress in a given direction with respect to the aforementioned two parameters for four alternative local forwarding rules. In particular, we evaluate the optimal performance in the complete network setting, whereas other studies focus on the local performance (single transmitter) in the so called heavy traffic limit (see related work). Exact analysis in the network setting is difficult and hence we have used simulation. Our baseline forwarding method is the deterministic greedy MFR. The second and the third algorithms attempt to spread traffic by randomizing the choice of the next hop. The fourth algorithm is based on ideas in [8] and opportunistically chooses the best available next hop.

Our main observations are the following. MFR has the weakest performance due to its poor ability to spread traffic, and it is shown that the upper bounds on performance derived in [2] are indeed quite loose. The randomized methods are able to spread traffic better and attain a better performance. Opportunistic forwarding performs clearly the best and achieves a four times as good performance as MFR. However, the opportunistic method and MFR are not directly comparable as the MAC protocol is also modified in the opportunistic scheme, as described later. Nevertheless the results demonstrate the considerable gains that can be achieved by using a jointly designed forwarding/MAC algorithm. We have also analyzed the distribution of packets in the network to confirm the claims about the abilities of the methods to distribute packets.

The paper is organized as follows. Section II presents our network model and the studied forwarding methods are described in Section III. Simulation related details are discussed in Section IV and our numerical results are in Section V. Finally, Section VI contains the conclusions.

A. *Related work*

MFR was proposed and analyzed in [2]. Their network model is essentially the same as ours, and the authors analytically derive the optimal number of nodes within a transmission range and the corresponding optimal transmission probability that maximize the so called mean progress of a packet. However, the results are obtained for a single node under the heavy traffic limit (all nodes have packets to send all the time) providing upper bounds on the achievable performance.

Similar analysis on the local heavy traffic performance is done in [11], where the Boolean interference model is replaced with a more realistic interference model taking into account signal-to-noise ratios. In the model the transmission powers are assumed to be independent and identically distributed between the nodes and the time slots. Several qualitative theoretical results are obtained but explicit results on the performance are given only for the case with exponentially distributed powers. The work in [11] has been continued further in [12] with analysis of the important special case with constant powers.

The idea of considering a large ad hoc network at the macroscopic and microscopic level is adopted from [9]. However, [9] studies the macroscopic problem and presents a general model for defining the optimal routes.

We develop a model under which the performance of the microscopic level forwarding rules can be compared under a minimal number of system parameters. Furthermore, we study the performance of several methods in a complete network, where as the analytical studies [2], [11] and [12] only consider MFR and analyze the local maximum performance under the heavy traffic limit.

II. Network model and performance evaluation methodology

We first give the decomposition of the problem and then our network model at the microscopic level.

A. Problem decomposition

We consider a multihop ad hoc network with a large number of nodes. Because of the large number of nodes, a typical distance between a randomly selected source-destination pair is much greater than a typical distance between neighboring nodes and a typical path in the network consists of a large number of hops.

In this setting, the routing problem with the objective of maximizing the total amount of traffic the network can carry under a given traffic pattern can be divided into two separate problems, those at macroscopic and microscopic levels, see [9]. At the macroscopic level the task is to achieve optimal load balancing by choosing the routes (considered as smooth geometric curves) such that the maximum traffic intensity over the network is minimized. The microscopic level considers the network at the scale of individual nodes. At this level, the problem is to determine local forwarding rules that maximize the packet flow in a given direction. The traffic flowing in different directions is handled by appropriate scheduling based on time sharing between different directions.

B. Microscopic level network model

The locations of nodes in the network are assumed to be distributed according to the two-dimensional Poisson point process with intensity λ [$1/\mathrm{m}^2$], We refer to the parameter λ as the node density. The network topology is static, and thus node mobility or failures are not considered in this study. Each node transmits with the same power resulting in a transmission range with radius R [m]. Interference occurs if a receiver hears more than one transmission inside its transmission range. Additionally, we fix the packet size and assume a slotted ALOHA type MAC protocol, where the nodes transmit in a time slot independently of others at probability p and successful transmissions are acknowledged. We assume that the acknowledgement packets are much smaller than data packets. Thus, the time slot duration is dominated by the transmission time of data packets.

It is assumed that in addition to its own coordinates, each node also knows the coordinates of its neighbors. A node can receive its coordinates from GPS and knowledge of the locations of the neighbors can be achieved with, e.g., simple local broadcasting. Using the location information and the direction in which a packet is traversing (as given by the macroscopic routing method), each node can make the forwarding decision (next-hop selection) locally. As a measure of progress in the forwarding, we use the distance that a forwarded packet travels along a given direction, i.e., the same as used in MFR (as discussed later). Additionally, we note that routing around concave nodes is a separate issue from the local forwarding rules, and hence it is assumed that concave nodes have been removed from the topology.

The performance of the forwarding methods is expressed as the mean progress of the packets (mean packet flow) in a given direction, similarly as in [2]. The analysis in [2] concerns the performance of a single node, and the mean progress D is defined as the average progress of a packet per time slot for an arbitrary node. It is measured in [m], its value depends only on N_R and p, and it can be expressed as

$$D(N_R, p) = \mathrm{P}\{\text{node transmits}\} \cdot \mathrm{P}\{\text{no collisions}\} \cdot \mathrm{E}[\text{progress of a packet}],$$

where $N_R = \lambda \pi R^2$, the average number of nodes within the transmission range, is a dimensionless parameter that we use instead of R. Assuming that all nodes always have data to send, i.e., $\mathrm{P}\{\text{node transmits}\} = p$ (heavy traffic approximation), in [2] an explicit expression is derived for $D(N_R, p)$.

In a network, the quantity of interest is the mean density of progress which is defined as the average progress of packets per unit time per unit area, and it is measured in [1/(m·s)]. Consider a differential area element dA. Thus, the mean number of nodes in dA equals $\lambda \cdot dA$, and the mean density of progress in a network, denoted by $I(N_R, p)$, is given by

$$I(N_R, p) = \frac{\lambda \cdot dA \cdot D(N_R, p)}{dA \cdot \Delta t} = \frac{\lambda}{\Delta t} \cdot D(N_r, p),$$

where Δt denotes the duration of the time slot. Note that $I(N_R, p)$ can be equivalently interpreted as the mean number of packets crossing a line of unit length perpendicular to the direction of progress. The heavy traffic assumption (all nodes have packets to send all the time), used in [2], [11] and [12], gives optimistic results for $D(N_R, p)$, since in a network with randomly located nodes some nodes become bottlenecks where packets are queuing while other nodes are idle. However, exact evaluation of $D(N_R, p)$ in a network is difficult, and hence we use simulation to estimate $I(N_R, p)$.

In practise it is convenient to work with dimensionless quantities to reduce the number of physical parameters. To this end, mean density of progress per node $D(N_R, p)$ has to be measured using a unit length related to the network model. In our network model, there are two possible length quantities: the transmission radius R and $1/\sqrt{\lambda}$, of which we have used the latter. Note that this choice is merely a convention and it has no impact on the results. The average distance between two nearest nodes is $1/(2\sqrt{\lambda})$, see [2], and consequently $\sqrt{\lambda} \cdot D(N_R, p)$

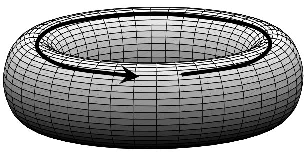

Fig. 1. Flow of packets in a torus.

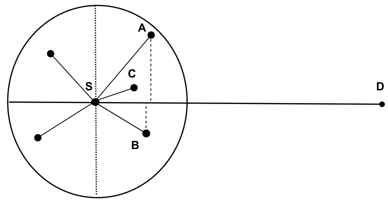

Fig. 2. Node S selects node A as the next hop in MFR.

is a dimensionless measure for the progress per node in terms of the mean number of nearest neighbor distances. Thus, by denoting $u(N_R, p) = \sqrt{\lambda} \cdot D(N_R, p)$, the mean density of progress per unit area equals

$$I(N_R, p) = \frac{\sqrt{\lambda}}{\Delta t} \cdot u(N_R, p). \quad (1)$$

For a fixed λ, since $N_R = \lambda \pi R^2$, optimizing R and p is equivalent to maximizing $u(N_R, p)$ with respect to N_R and p. As a function of λ there is no optimum; the higher the node density λ the higher is $I(N_R, p)$.

C. Simulation model

We maximize $u(N_R, p)$ via simulations. To this end, we simulate a finite area representing a snapshot of a large (infinite) network. To minimize simulation work, we try to keep the dimensions of the area as small as possible relative to the node density λ. However, this introduces the problem of border effects: nodes near the border of the network see different traffic and interference patterns than nodes in the middle of the network. To avoid harmful border effects we fold the plane into a torus, where routes may cross over the boundary of the plane and continue on the opposite side. In the simulations, the torus is formed from a unit square.

Furthermore, in a large network, individual nodes are carrying only relayed traffic, i.e., traffic originating from other nodes. Thus, in a small snapshot of a large network, the progress of the packets comes from traffic simply flowing through the network, i.e., there are no traffic sources or sinks. In order to find the greatest sustainable density of progress, we simulate the network under saturated traffic conditions. To this end, a large number of packets are placed in the network. During the simulation, the packets flow through the network in a given fixed direction, no packets are lost and no new packets are injected, i.e., the network is considered as a closed queuing network. Saturated traffic in this case means that the number of packets circulating in the network is large enough such that a further increase in the packets would have no substantial effect on $I(N_R, p)$. The flow of packets in the torus is illustrated in Figure 1.

In our simulations, λ is a given system parameter and also Δt is fixed, and maximizing $I(N_R, p)$ is equal to maximizing $u(N_R, p)$, see (1). To estimate $u(N_R, p)$, we average over several realizations of random networks, with nodes distributed according the spatial Poisson process with intensity λ. To vary the value of N_R, we change the value of R. For each realization, N randomly placed nodes are created and M packets are placed in each node, and the simulation time is T time slots (after initial transient). During the simulation each packet i travels a distance S_i. Thus, we estimate $u(N_R, p)$ by

$$u(N_R, p) = \sqrt{\lambda} \cdot \frac{1}{T \cdot N} \sum_{i=1}^{N \cdot M} S_i,$$

where $\frac{1}{T \cdot N} \sum_i S_i$ is an estimate of $D(N_R, p)$. The task is to find such N_R and p that maximize $u(N_R, p)$ in a given direction for a given local forwarding method. Different forwarding methods can then be compared using the maximum $u(N_R, p)$ as a performance measure.

III. Forwarding methods

In this section, we define the four different forwarding methods that are compared in our simulations.

A. Most forward within radius

MFR was the first proposed geographic forwarding method in the literature. It is a simple greedy method, where packets are always forwarded to the neighbor for which the length of the projection of the vector pointing at the neighbor onto a vector pointing in the given direction is the greatest, see Figure 2. In our simulations, traffic flow is from left to right and the next hop is the neighbor with the greatest x-coordinate. If there are no neighbors with a positive progress, i.e., no forward neighbors, the neighbor with the least negative progress can be chosen. This may be beneficial, but usually the result is a local routing loop between a concave node and its backward neighbor. However, since we are assuming that concave nodes are eliminated from the topology, the formation of loops is not a problem in our simulation.

In a static network with packets progressing in the same direction according to MFR, packets flow along certain paths. This is easy to see in our torus model in

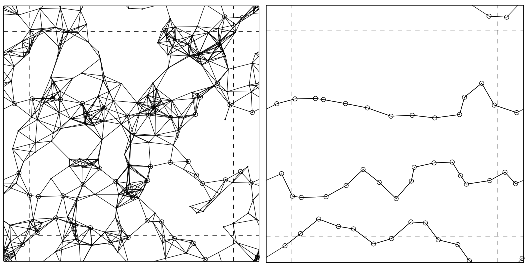

Fig. 3. A random network and all its links (left) and the three MFR paths in the network (right).

which initially a given number of packets is placed in all nodes and no new packets are generated. After the initial transition, all packets traverse along deterministic paths, which we call MFR paths. Thus, only a fraction of the nodes are actively taking part in the forwarding, which also partly explains the poor performance of MFR. This is illustrated in Figure 3, where the left figure shows a realization of a random network and all the links in it, and the right figure depicts the resulting MFR paths. In both figures, the border areas, from which it is possible to have a link to the opposite side of the network, are marked with dashed lines. Note that it is also possible that a given MFR path goes around the torus multiple rounds before returning to a starting node. The formation of MFR paths is not an artefact of the torus. In a large network, where almost all traffic is relayed traffic, the traffic will be concentrated on MFR paths.

B. Random forwarding

As discussed, MFR does not distribute traffic efficiently. The easiest way to achieve better spreading of the traffic at the microscopic level is to randomize the local forwarding decision. In random forwarding, each forward neighbor has an equal probability of being a next hop. More precisely, the probability q_{ij} that sending node i chooses a forward neighbor j as a next hop equals

$$q_{ij} = \frac{1}{N_F},$$

where N_F is the number of all forward neighbors. Random forwarding spreads the packet flow effectively over the whole network, but the cost of better utilization of the network is that some of the hops are very short.

C. Weighted random forwarding

The idea of weighted random forwarding (WRF) is to increase the average hop length of random forwarding by weighting the next hop probabilities depending on the locations of the neighbors. Thus, in weighted random forwarding, the probability q_{ij} that sending node i chooses a forward neighbor j as a next hop equals

$$q_{ij} = \frac{l(i,j)}{\sum_{k=1}^{N_F} l(i,k)},$$

where $l(i,j)$ denotes distance between nodes i and j.

D. Opportunistic forwarding

If the MAC protocol assumption is partly relaxed, it is possible to devise an opportunistic forwarding algorithm. The idea is to implement a mechanism that allows the selection of the best available receiver among the nodes that can successfully receive the packet. Our opportunistic forwarding is a modified version of ExOR [8], and its operation during a time slot is as follows:

1) At the beginning of a time slot, a sender broadcasts a packet to all its forward neighbors with probability p. The sender includes a forward neighbor list that is prioritized by progress into the packet.
2) All forward neighbors not hearing another transmission receive the packet. Each forward neighbor prepares to send an ACK after a delay proportional to its position in the forward neighbor list.
3) ACKs are sent. A forward neighbor hearing an ACK with higher priority than its own cancels its scheduled ACK. Sender hears at least one ACK.
4) The sender sends a permission to send (PTS) packet to the neighbor from which it received the highest priority ACK.
5) The neighbor that got the PTS stores the packet in its queue. Other forward neighbors drop the packet.

In our opportunistic forwarding, a sender makes the decision of the next hop based on received acknowledgements. The acknowledgement scheme of ExOR is not used because it cannot guarantee the absence of duplicate packets. Opportunistic forwarding increases the amount of control traffic compared to ExOR and the basic slotted ALOHA. However, it is assumed that this has no significant effect on the time slot duration, which is is dominated by the transmission time of data packets.

Because the medium access in opportunistic forwarding does not strictly follow the slotted ALOHA protocol, the mean density of progress of opportunistic forwarding is not directly comparable to the three previous algorithms. Nevertheless, opportunistic forwarding gives a good approximation of the upper limit performance in our network model for a contention-based MAC scheme.

IV. Practical simulation issues

Here we summarize some practical issues related to determining the simulation parameters.

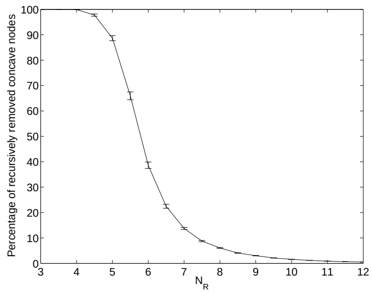

Fig. 4. The percentage of recursively removed concave nodes as a function of N_R with $\lambda = 1000$ [1/unit area]. The 95% confidence intervals are shown as error bars.

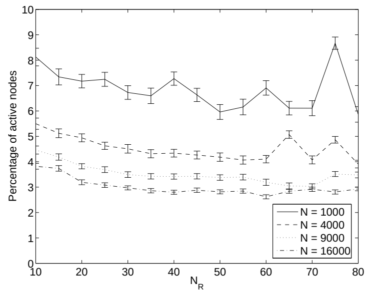

Fig. 5. The mean percentage of active nodes averaged over 200 different node location realizations as a function of N_R. The 95% confidence intervals are shown as error bars.

A. Removal of concave nodes

As it was already stated we assume that concave nodes are removed from the network, thus eliminating the need for a method to route around concave nodes. In our setting of a fixed direction for the traffic flow it is easy to remove concave nodes recursively by inspecting in each round if each node has at least one forward neighbor and eliminating those that do not. To analyze the importance of the concave node effect, in Figure 4 we have plotted the percentage of concave nodes as a function of N_R when $\lambda = 1000$ [1/unit area]. For each value of N_R, 1000 different node location realizations were created. Note that for dense networks ($N_R > 10$), which is the case we are studying, it is common that there are only a few or no concave nodes.

B. Sufficient number of nodes

For a given fixed area in the simulations that is then folded to a torus surface, the problem is that depending on the number of nodes placed in the area, the torus network may also cause "border" effects. In practise, we needed to carefully select the number of nodes to fulfill the assumption of a large network and to keep computation times feasible.

Recall that the torus in the simulations is formed from a unit square. Initially, for each network realization we placed $N = 1000$ nodes uniformly in the area (essentially corresponding to a realization from a Poisson process with $\lambda = 1000$ nodes per unit area). This value was sufficient in random forwarding, WRF and opportunistic forwarding. However, in simulations of MFR, $N = 1000$ was too small and caused unexpected variations in the MFR path formation. This is illustrated in Figure 5 in which the mean percentage of active nodes (i.e., nodes that are part of the MFR paths) averaged over 200 different network realizations is plotted as a function of N_R for different values of N. The overall declining trend of the curves flattens and the unexpected variations are decreased as N is increased. However, the computation time becomes rapidly infeasible as N is increased. We made a tradeoff between accuracy and computation time by choosing $N = 9000$ nodes to be used in the MFR simulations.

C. Saturated load and initial transient length

In each simulation we consider a fixed value of p and N_R and the aim is to determine the mean density of progress under saturated traffic conditions. To this end, initially the same number of packets, M, were placed in each active node (i.e., those nodes that were left after removal of concave nodes), and a value for M needed to be chosen such that a further increase would have no significant effect on $u(N_R, p)$. However, making M arbitrarily large entails very long initial transient periods until the packet flow reaches a stationary state. Thus, to keep simulation time manageable, M and the initial warm-up periods needed to be carefully determined.

V. Numerical results

Based on the discussion in Section IV, the parameter values used in the simulations are given in Table I. Recall that the unit of λ is nodes/unit area, unit of M is packets, time is expressed in number of time slots, and the torus area corresponds to the unit square.

A. Optimization of mean density of progress

The purpose of the simulations is to maximize the dimensionless mean density of progress $u(N_R, p)$ with respect to p and N_R for different local forwarding rules. N_R is varied by keeping λ constant and changing the value of R. The dimensionless mean density of progress $u(N_R, p)$ is depicted as a function of p for each forwarding algorithm in Figure 6. The results from the figures are summarized in Table II in which the

TABLE I

THE USED PARAMETERS FOR EACH SIMULATION SCENARIO

	MFR	Random forwarding	WRF	Opportunistic forwarding
λ	9000	1000	1000	1000
M	50	50	50	50
p	[0.15,0.45]	[0.05,0.50]	[0.05,0.50]	[0.25,0.60]
N_R	[20,60]	[10,18]	[10,18]	[12,20]
Transient duration	100000	600000	800000	1000000
Total sim. time	400000	1200000	1600000	2000000
Nof network realizations	200	50	50	50

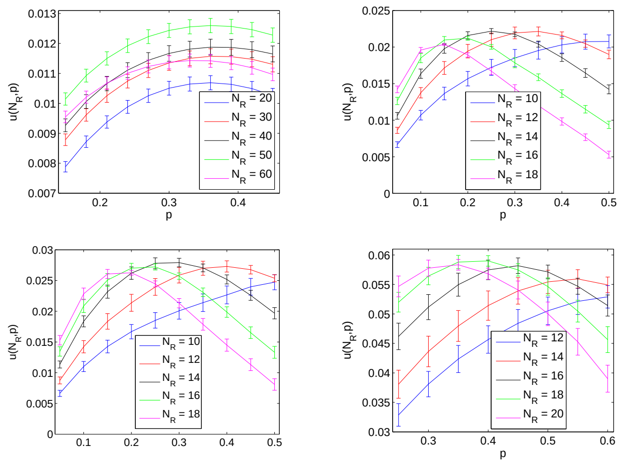

Fig. 6. The dimensionless mean density of progress $u(N_R, p)$ as a function of p for MFR (upper left), random forwarding (upper right), WRF (lower left) and opportunistic forwarding (lower right). The 90% confidence intervals are shown as error bars.

maximum $u(N_R, p)$ and corresponding N_R and p values are collected for each forwarding algorithm.

As can be seen from Table II, MFR has the worst $u(N_R, p)$ and the optimal N_R is much greater than with other methods. This is due to the formation of MFR paths resulting in low network utilization. Random forwarding spreads traffic effectively over the whole network. Better utilization of network resources results in an almost doubled value for $u(N_R, p)$ compared to that of MFR. WRF is able to improve the performance of random forwarding by weighting the next hop probabilities with the relative progress. This results in longer mean hop lengths and better average progress. The curves in Figure 6 for random forwarding and WFR have very similar shapes, only the optimal p for each N_R is somewhat higher in WRF. This may be partly due to the existence of nodes in WRF that receive packets rarely and that can consequently sustain higher transmission probabilities.

As expected, opportunistic forwarding achieves clearly the best $u(N_R, p)$. It should be noted that the performance of opportunistic forwarding is not directly

TABLE II

THE MAXIMUM $u(N_R, p)$ FOR EACH FORWARDING METHOD.

	$u(N_R, p)$	N_R	p
MFR	0.0126	50	0.35
Random forwarding	0.0222	14	0.25
WRF	0.0279	14	0.3
Opportunistic forwarding	0.0590	18	0.4

comparable to the other forwarding methods because, unlike others, it combines the operation of a slotted MAC protocol with the forwarding method. Opportunistic forwarding always sends a packet to the most forward neighbor that is able to receive the packet (the other methods do not use information about the state of other nodes). Thus, collisions are rarer and the optimal values of N_R and p are higher than in random forwarding and WRF. Never the less, the opportunistic method clearly demonstrates the benefits of using local coordination.

We can also compare our results to the analytic results in [2]. Their results show that the maximum dimensionless mean density of progress $u^*(N_R, p) = 0.0431$ is achieved with $N_R^* = 7.72$ and $p^* = 0.113$. Our simulated values for MFR, random forwarding and WRF are significantly smaller than $u^*(N_R, p)$ because the heavy traffic assumption used in [2] is overly optimistic in a network setting. Only opportunistic forwarding achieves a greater maximum $u(N_R, p)$ than $u^*(N_R, p)$ due to the different and more efficient MAC scheme. Also, our optimal N_R and p for all forwarding methods are greater than N_R^* and p^* since in a network the heavy traffic assumption is unrealistic and the presence of idle nodes allows a substantially greater N_R and p.

B. *Distribution of packets in the network*

To further analyze the ability of the studied forwarding methods to distribute traffic in the network, we have also examined the distribution of packets in the network. We divided the network in a 10×10 grid and averaged the number of packets in each square over 10 snapshots taken during a simulation for one network realization. Furthermore, we use the same realization for the random forwarding, WRF and opportunistic forwarding to facilitate comparisons. For these methods the realization was generated with network density $N_R = 14$ corresponding to the optimal density for random forwarding and WRF. For the values of p for each method, we used the optimal values from Table II. For opportunistic forwarding the density is not optimal, but its performance with $N_R = 14$ is quite close to that. For MFR the realization was generated with $N_R = 50$ ($N_R = 14$ is too small for MFR to operate reasonably).

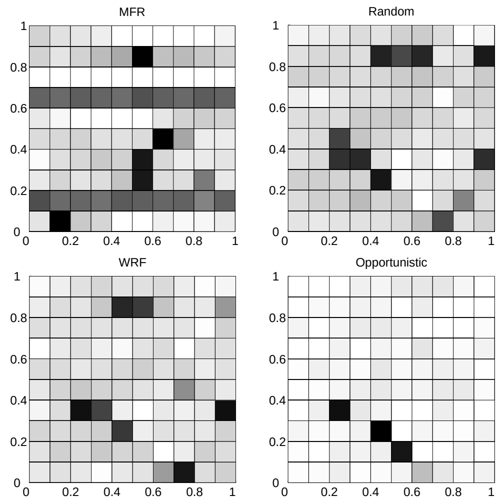

Fig. 7. The mean number of packets within a square area in the network. The shading of a square corresponds to the number of packets in that square in the logarithmic scale.

The results are shown in Figure 7. The shading of a square corresponds to the number of packets in that square in the logarithmic scale. Totally white areas correspond to empty areas and dark areas to very highly loaded areas (with hundreds of buffered packets). As can be seen, random forwarding and WRF succeed better in traffic spreading than opportunistic forwarding (the area is more uniformly grey). The formation of MFR paths is also visible (e.g., the two dark strips with high load). Opportunistic forwarding concentrates traffic resulting in a few very big bottleneck areas. However, experiments with other network realizations showed that the bottleneck behavior in opportunistic forwarding was not always as clear as in this example. Further study would be needed to more thoroughly analyze the traffic distribution aspects of the forwarding methods.

VI. Conclusions

We have used a network model under which the macroscopic level routing problem and the microscopic level forwarding problem can be decoupled from each other, and the performance of the local forwarding methods can be compared under a minimal set of parameters. In this case, the performance can be expressed as the mean density of progress and it depends on two parameters: the transmission radius of the nodes and the probability to transmit in a time slot. With respect to these two parameter, we have analyzed via simulations the maximum mean density of progress of four different forwarding methods: MFR, random forwarding, WRF, and the locally coordinated opportunistic scheme. In particular, the performance of the methods has been evaluated in a network setting.

Our results show that MFR suffers from concentrating the traffic onto certain deterministic paths. The randomized methods are able to spread the traffic more efficiently and achieve a better performance. However, almost four times as good performance as with the deterministic approach is obtained with the opportunistic method, where the MAC layer is enhanced with functionality to always send the packet to the best receiver, demonstrating the benefits of local coordination.

Suggestions for further research include the following. As seen in the results, the problem of bottlenecks exists to some extent in all the methods and more adaptive methods can be developed to alleviate this, cf. [5]. Also, similar forwarding methods can be developed for other MAC protocols, e.g., CSMA-like protocols, as well as, new ways for achieving local coordination.

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