Geographic Random Forwarding (GeRaF) for Ad Hoc and Sensor Networks: Multihop Performance

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Abstract—In this paper, we propose a novel forwarding technique based on geographical location of the nodes involved and random selection of the relaying node via contention among receivers. We focus on the multihop performance of such a solution, in terms of the average number of hops to reach a destination as a function of the distance and of the average number of available neighbors. An idealized scheme (in which the best relay node is always chosen) is discussed and its performance is evaluated by means of both simulation and analytical techniques. A practical scheme to select one of the best relays is shown to achieve performance very close to that of the ideal case. Some discussion about design issues for practical implementation is also given.

Index Terms—Geographic forwarding, multihop performance, ad hoc networks, sensor networks, energy, routing, MAC.

1 Introduction

Ad hoc and sensor networks are recently attracting a lot of interest in the research community.[1] One of the main issues here is the necessity to save energy since the nodes are usually battery powered and need to be alive for a relatively long time. A few papers have recently appeared which propose MAC, routing, and topology maintenance schemes that try to save energy based on aggressive power-off strategies. In fact, it has been recognized that the only way a node can save substantial energy is by powering off the radio since transmitting, receiving, and listening to an idle channel are functions which require a comparable amount of power. As a consequence of this key observation, MAC and routing strategies need to be revisited since, for example, CSMA-based access schemes need all nodes to continuously listen to the channel while, on the other hand, nodes which power off their radio may end up not being reachable and/or aware of activity in the network. The main problem in this scenario is therefore that of combining protocols which minimize the amount of time the radio is on with effective strategies for MAC and routing.

Here, we propose Geographic Random Forwarding (GeRaF, pronounced as "giraffe"), a novel transmission scheme based on geographical routing where packets are relayed on a best-effort basis, i.e., the actual node which acts as a relay is not known a priori by the sender, but rather is decided after the transmission has taken place. This idea leverages on the fact that, in the wireless environment, broadcast is free (from the sender's point of view) and that, in the presence of randomly changing topologies, a node may not be aware of which of its current neighbors is in the best position to act as a relay. In a sense, this is like doing contention at the receiver's end, which is untraditional because, in classic schemes, it is the transmitter which contends for the channel. Here, since the intended recipient is not specified, multiple nodes may be able to receive the packet and a *receiver contention scheme* is therefore needed to guarantee that a single relay is chosen, thereby avoiding packet duplication.

In this paper, we focus on the multihop performance of such a solution, in terms of the average number of hops to reach a destination as a function of the distance and of the average number of available neighbors. An idealized scheme (in which the best relay node is always chosen) is discussed and its performance is evaluated by means of both simulation and analytical techniques. A practical scheme to select one of the best relays is shown to achieve performance very close to that of the ideal case. Even though not the major focus of this paper, we provide some discussion about practical issues and briefly outline a possible protocol based on the main ideas presented in this paper. Such protocol is described and analyzed, in detail, in a companion paper [1].

1.1 Related Work

An example of how topology can be maintained in the presence of sleeping nodes is provided by SPAN in [2], where the authors propose that, in a dense network, several disjoint sets of nodes be identified, each able to guarantee connectivity and bandwidth to all nodes. As long as one of these sets is active at any given time, the network is connected; on the other hand, since when one set is active the others can sleep, the percentage of time a node must be active is drastically reduced.

1. While, in this paper, we will mostly refer to sensor networks, many of the ideas presented can also be applied to ad hoc networks.

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STEM [3] provides a way to establish communications in the presence of sleeping nodes. Each sleeping node wakes up periodically to listen. If a node wants to establish communications, it starts sending out beacons polling a specific user. Within a bounded time, the polled node will wake up and receive the poll, after which the two nodes are able to communicate. An interesting feature of STEM is that a dual radio setup is envisioned with separate frequencies used for wakeup and actual data transmission.

GAF [4] is similar to SPAN in a sense since it envisions the use of only a fraction of the nodes at any given time. The specific approach of GAF is to divide the area in square regions, called grids, in such a way that any two nodes in neighboring grids are within range of each other. With this provision, grids can be treated as equivalent (or virtual) nodes, in the sense that all nodes in the same grid can be interchangeably used for routing purposes. The price to pay for this guarantee is that the hop length is significantly smaller than the radio range (by a factor of $\sqrt{5}$, which is the largest possible distance between two nodes in adjacent grids [4]). This may result in inefficiency in terms of latency and energy consumption (more hops than possibly needed).

Studies where the relationship between transmit power and connectivity is explored, e.g., by evaluating how the radio range should be chosen or how many neighbors a node should have, can be found in [5], [6], [7]. The effect of multihop operation and the related trade offs in terms of energy consumpion are explored in [8]. Ways to build minimum energy networks and the complexity of some associated algorithms are studied in [9]. Other contributions on connectivity and power-efficient topologies include [7], [10].

As to MAC schemes, most papers in the literature assume either TDMA-based schemes [11], [12] or multichannel setups in which parallel transmissions can be performed without interference [13], [14] or variants of classic contention-based schemes, usually based on RTS/CTS handshake in order to mitigate the hidden terminal problem [15], [16].

A number of recent papers also propose specific energy efficient routing schemes for sensor networks. The authors of [17], [18] propose LEACH, which is a cluster-based routing protocol in which the role of clusterhead is rotated among the sensor nodes to avoid stressing only some of them. An improvement of LEACH, called PEGASIS, which is chain-based and provides near optimum energy and delay performance is proposed in [19]. Similarly, energy aware routing [20] avoids using the lowest-energy routing paths consistently, as this may lead to energy depletion of nodes in key locations; instead, it allows the use of suboptimal paths. Routing is coupled with a thresholding mechanism in [21], [22], where transmissions are inhibited when the sensed attribute is not significant or not significantly different from what sensed/transmitted in the past, thereby reducing the transmission/relaying activity of nodes. A routing scheme which minimizes the control traffic in the network is proposed in [23]. Traffic shaping to make the network load more uniform, thereby improving the energy utilization of the nodes in the network, is proposed in [24]. An algorithm based on constrained shortest paths, which tries to minimize energy consumption while retaining good end-to-end performance, is proposed in [25]. The authors of [26] introduce the maximum flow-life curve as the routing objective and propose a new routing scheme based on this concept. Techniques to improve packet forwarding in sensor networks are proposed in [27] (using minimum cost paths) and in [28] (using multicast trees). The authors of [29] propose modifying the sensor node layering architecture so that forwarding decisions can be made by the hardware, thereby greatly improving the energy (and latency) performance of the overall system.

Routing protocols based on geographic information have been considered in the past. GPSR [30] is a scalable greedy algorithm with the ability to go around low-density network regions. GEAR [31] also uses geographic information to deliver packets to a certain service region (rather than to a specific node). Other protocols, which make use of geographic information to improve efficiency, include LAR [32] and DREAM [33].

A common characteristic of the above schemes is that, at the MAC layer and often also at the routing layer, when a node decides to transmit a packet (as the originator or a relay) it specifies the MAC address of the neighbor to which the packet is being sent. (Notable exceptions are GRAdient Broadcast [34] and Gradient Routing [35].) Knowledge of the network topology (though in many cases only local in extent) is required since a node needs to know its neighbors and possibly some more information related to the availability of routes to the intended destination. This topological information can be acquired at the price of some signaling traffic and becomes more and more difficult to maintain in the presence of network dynamics (e.g., nodes which move or turn off without coordination).

2 Geographic Random Forwarding: Basic Idea

We assume that each node has some knowledge of its own position and of the position of the sink node, i.e., the node where the information needs to be delivered. For simplicity of description, we assume that this location information is perfect (some results for imperfect location information will be presented in Section 5) and that propagation can be characterized in terms of coverage circles (that is, two nodes are neighbors if they are within the coverage radius of each other). While this is certainly a crude model for propagation, it is assumed here as a first step toward understanding fundamental behaviors. Extension to more realistic models, e.g., including Rayleigh fading, is being studied. Preliminary results show that an approach accounting for Rayleigh fading leads to results that are very similar to those presented here.

The basic idea is the following: Once a node has a packet to send, it sends it using some type of broadcast address while specifying its own location and the location of the intended destination. All active (listening) nodes in the coverage area will receive this packet and will assess their own priority in trying to act as a relay, based on how close they are to the destination. The message can be the full packet or an RTS message if a collision avoidance mechanism is used. These considerations are ignored here, where we are concerned with the multihop performance of the scheme.[2] More details about an actual protocol based on collision avoidance can be found in Section 5 and in [1].

As a first step, suppose a mechanism is in place to make sure that the relaying node is, in fact, the one closest to the destination. The MAC/routing scheme then continues similarly. The relayed packet is, in turn, sent to a broadcast address and contains the locations of the transmitter and of the final destination, thereby providing a means to geographically route it without any routing tables or topological information (except for the location of the destination). The scenario we have in mind is one in which sensor nodes may be stationary and densely deployed and randomly turn on and off, thereby providing a random topology. If the density of active nodes is appropriate, it is likely that the node closest to the destination will be almost the best possible, i.e., will provide an advancement toward the destination close to the coverage radius. In this case, there is no need for sleeping nodes to coordinate (they can turn on and off randomly). Also, since no attempt is made to gain topology information, the frequency at which nodes turn on and off may be fairly high, which provides for small latencies.[3]

Notice also that the fact that we do not address a specific node allows us to use one of the first available nodes within the coverage area, as opposed to STEM, in which we have to wait for a specific node to wake up. In this case, we can easily decrease the duty cycle of each node without increasing latency if the node density is adequate. In fact, the rate at which any of N nodes wakes up is N times that of each single node and, therefore, we can maintain similar network connectivity while saving more energy if we increase N and decrease the wakeup rate by keeping their product constant.

It should be observed at this point that GAF [4] tries to achieve a similar objective by making all nodes in each grid interchangeable from a routing perspective. However, a major weakness of GAF's approach is precisely the requirement that this routing feature be guaranteed, which forces hops to cover less than half the distance allowed by the radio range.

3 Multihop Analysis

Consider the following simple scenario: A source wants to deliver a packet to a destination in the absence of cross traffic (which corresponds to the case in which the network is mostly monitoring, and occasionally a message is generated). Nodes are randomly placed in the region according to a Poisson process with density ρ nodes per unit area. This model is adequate in situations in which

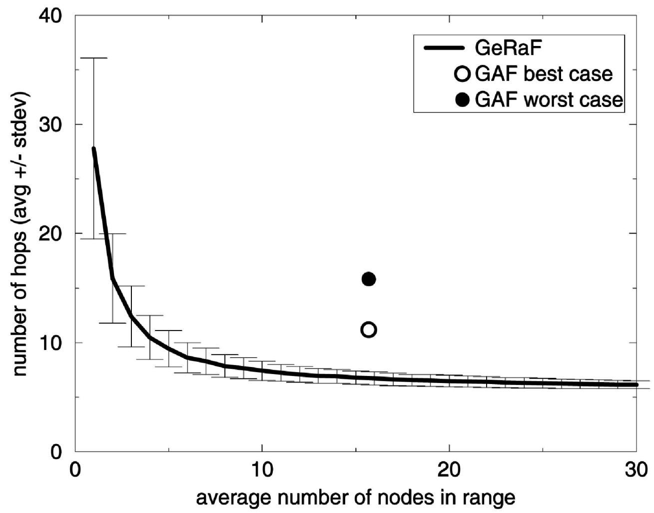

Fig. 1. Average number of hops $\pm$ standard deviation versus average number of active neighbors. Distance $D = 5$.

nodes are randomly deployed and is also appropriate for a first evaluation of the performance of our scheme. Due to the use of sleep modes, each node is available as a relay with probability d so that the density of actually available nodes is $M' = d\rho$. Let the radio range be normalized to 1 and let D be the distance between the source and the destination. Finally, let $M = d\rho\pi$ be the average number of available relays in the coverage area.

We initially assume an ideal operation whereby the neighbor closest to the destination (if any) is, in fact, selected as the relaying node unless the destination itself is within range, in which case the packet is directly delivered. We are interested in computing the number n of hops necessary to reach the destination as a function of the distance D and of the density of active nodes M'. Clearly, it must be $n \geq D$ and we expect that $\lim_{M' \to \infty} n = \lfloor D + 1 \rfloor$.

We set up a simple simulation to evaluate the number of hops which are necessary to reach the destination. We assume first that the transmit node is at distance D from the final destination. We randomly position a Poisson distributed number of relays (with average M) in the coverage area and, among them, we select the one that is closest to the destination, which, in turn, becomes the transmit node for the next hop. This step is repeated (using the new distance to the destination instead of D) until a relay within range of the destination is reached from which a single hop is needed. If it happens that there are no nodes in range which are closer to the destination than the transmit node, one hop is counted, but the position of the transmit node is not updated. This corresponds to the fact that, if no relays are present to provide advancement toward the destination, a transmit node would try again and, in the next attempt, the set of possible relays is independently generated so that, with probability one, the packet arrives to the destination in a finite amount of time.

The observed behavior is shown in Figs. 1, 2, and 3, where simulation results for the average number of hops (with bars denoting the standard deviation) are plotted versus the node density, expressed in terms of the average number of active neighbors, M. The expected behavior is

2. The only aspect of MAC which may impact our analysis is the effectiveness of the selection mechanism, which, if not properly designed in some cases, may lead to using the "wrong" relay, which would degrade the multihop performance. Other MAC details (e.g., backoff mechanisms, handshakes, contentions, etc.) have essentially no impact on the number of hops needed to reach the destination, though they obviously affect delay and energy constraints.

3. The limiting factor in this case is likely to be in the hardware capabilities (e.g., agility of the transceiver).

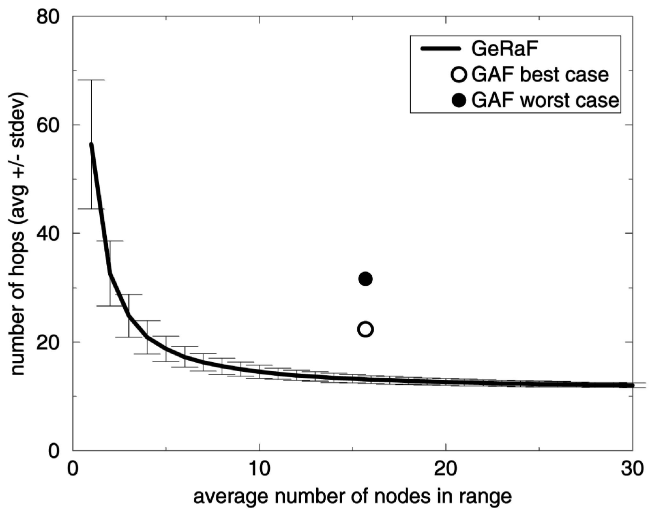

Fig. 2. Average number of hops $\pm$ standard deviation versus average number of active neighbors. Distance $D = 10$.

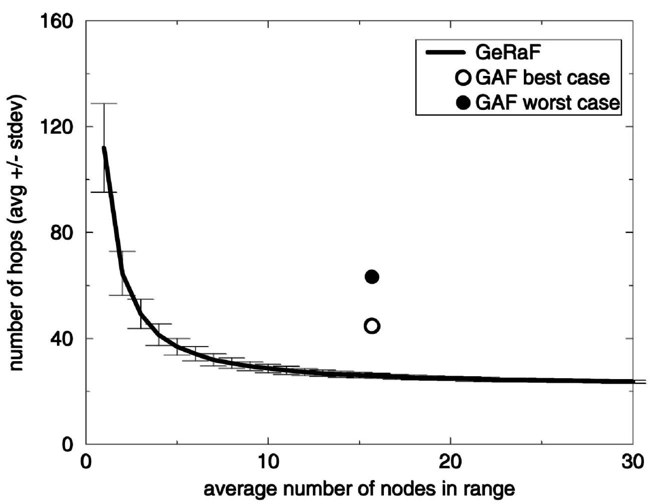

Fig. 3. Average number of hops $\pm$ standard deviation versus average number of active neighbors. Distance $D = 20$.

observed. Interestingly, the results for different distances scale proportionally to the distance itself. While this is intuitive, the fact that the scaling is almost exactly proportional was not entirely obvious.

In GAF, which is the only other scheme with which we can compare directly, the area is divided into square grids of side $r = 1/\sqrt{5}$ (normalized to radio coverage). Notice that, if we consider all nodes in a grid as a single equivalent node located at its center, each hop corresponds to a distance of exactly r. This distance is not necessarily the advancement toward the destination as this depends on the relative orientation of the source-destination direction and the grid layout. In the best case (they are parallel), one hop leads to an advancement of r units toward the destination, whereas, in the worst case (they form a 45^o angle), the one-hop advancement is $r/\sqrt{2} = 1/\sqrt{10}$ (which is three times shorter than allowed by the radio range).

Regarding active node density, GAF requires that at least one node be present in each grid, which corresponds to an average node density of at least one in each $1/5$ square unit area, i.e., 5π nodes within radio range. According to the above discussion, the isolated points shown in the graph correspond to the best-case and worst-case performance of GAF.

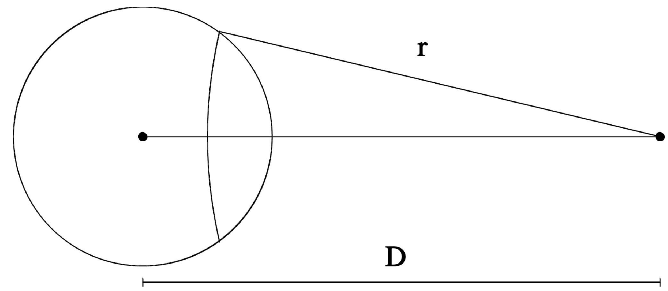

Fig. 4. Circle intersection for the analysis.

Notice that the curve for our optimal scheme lies well below and to the left of GAF's points, which means that, for comparable active node density (i.e., overall energy consumption due to sleep duty cycle), we can deliver a packet in much fewer hops (which is an effect of GAF's underutilization of radio coverage) or, equivalently, for a given number of hops to the destination (which corresponds to latency, as well as transmission energy used to deliver a packet), we need much fewer nodes within range and this corresponds to a reduced duty cycle given the same density of physical nodes. Note that the points corresponding to GAF do not take into account details such as synchronization and coordination issues among nodes and the possibility of some grids being empty and, therefore, are to be seen as somewhat optimistic estimates of GAF's performance. The curves for GeRaF are themselves idealized, but, as shown later, a practical scheme would perform almost as well.

3.1 Simple Analytical Bounds on the Multihop Performance of GeRaF

In this section, we approach the problem of evaluating the multihop performance of random forwarding using analytical techniques for the ideal case in which the best possible relay is selected.

Consider the case in which a node needs to send a packet to a destination which is at distance D (all distances are normalized to the coverage radius, which is therefore taken to be unity). Let γ be the remaining distance after one hop, which must satisfy $D - 1 \leq \gamma \leq D$. The probability distribution of γ depends on the area of the intersection between two circles with centers at distance D and with radii 1 and r, respectively. More specifically, the probability that the remaining distance γ is at least r is the probability that the intersection of the two circles contains no relays (see Fig. 4). If $A(r, D)$ is the area of the intersection, we have

$$P[\gamma \geq r] = e^{-MA(r,D)/\pi}, D - 1 \leq r < D, \tag{1}$$

$$P[\gamma = D] = e^{-MA(D,D)/\pi}, \tag{2}$$

where we account for the fact that, if the whole relay region is empty, there is no advancement and the remaining distance does not change.

By geometric considerations, the area in question is found as

$$A(r,D) = 2\int_{D-1}^{r} a \arccos\left(\frac{a^2+D^2-1}{2aD}\right) da = \beta(w,1) + \beta(D-w,r), \tag{3}$$

in which

$$w = \frac{D^2 - r^2 + 1}{2D} \tag{4}$$

and

$$\beta(x,y) = \frac{1}{2}\left(\pi - 2\arcsin\frac{x}{y} - 2\frac{x}{y}\sqrt{1-\left(\frac{x}{y}\right)^2}\right). \tag{5}$$

The advancement toward the destination is $\zeta = D - \gamma$, with probability distribution

$$P[\zeta \le a] = \begin{cases} e^{-MA(D-a,D)/\pi} & 0 \le a \le 1 \\ 0 & a < 0 \\ 1 & a > 1. \end{cases} \tag{6}$$

Let

$$f_\zeta(a) = f_\zeta^c(a) + P[\zeta = 0]\delta(a) \tag{7}$$

be the pdf of the advancement, where $f_\zeta^c(a)$ is the derivative of $P[\zeta \le a]$ in $a \in (0,1)$. The average advancement is then found as

$$\begin{aligned} E[\zeta] &= \int_0^1 a f_\zeta(a) da = \int_0^1 a f_\zeta^c(a) da \\ &= a e^{-MA(D-a,D)/\pi}\Big|_{a=0}^{a=1} - \int_0^1 e^{-MA(D-a,D)/\pi} da \\ &= 1 - \int_0^1 e^{-MA(D-a,D)/\pi} da. \end{aligned} \tag{8}$$

Notice that ζ depends on D. More precisely, it can be shown that ζ is an increasing function of D.

We now would like to find the average number of hops which are necessary in order to reach a destination at distance D. Note that, from any point in the coverage area of the destination, only a single hop is necessary. The total number of hops is then $n = n' + 1$, where n' is such that the first n' hops lead to a point which is within coverage of the destination while the first $n' - 1$ hops do not. More precisely, if X_i is the advancement corresponding to the ith hop, n' is such that

$$\sum_{i=1}^{n'-1} X_i < D - 1 \le \sum_{i=1}^{n'} X_i. \tag{9}$$

Consider a slightly different problem in which, instead of X_i, we have Y_i, where the Y_is are independent and identically distributed (iid) random variables such that $Y_i \in [0,1]$. In this case, we can apply results from the theory of stopped random walks [36]. The random variable n' is a stopping time for the sequence Y_i and, therefore, we have [37]

$$E\left[\sum_{i=1}^{n'} Y_i\right] = E[n']E[Y] \tag{10}$$

and, from the rhs inequality, we obtain

$$E\left[\sum_{i=1}^{n'} Y_i\right] \ge D - 1 \Longrightarrow E[n'] \ge \frac{D-1}{E[Y]}. \tag{11}$$

The same technique cannot be applied to the lhs inequality since $n' - 1$ is *not* a stopping time for Y_i. However, since $Y_i \in [0,1]$, we have that

$$\sum_{i=1}^{n'} Y_i \le \sum_{i=1}^{n'-1} Y_i + 1 < D \tag{12}$$

from which we obtain

$$E\left[\sum_{i=1}^{n'} Y_i\right] < D \Longrightarrow E[n'] < \frac{D}{E[Y]}. \tag{13}$$

We then obtain that the average number of hops $E[n] = E[n'] + 1$ can be bounded as

$$\frac{D-1}{E[Y]} + 1 \le E[n] < \frac{D}{E[Y]} + 1. \tag{14}$$

The above results cannot be directly applied to our problem since the random variables X_is are not iid. However, the advancement toward the destination is a nondecreasing function of the distance D in the sense that

$$P[\zeta(D_1) > a] \ge P[\zeta(D_2) > a], \text{ if } D_1 \ge D_2. \tag{15}$$

This fact can be seen as follows: First, note that

$$P[\zeta(D) \le a] = e^{-MA(D-a,D)}, 0 \le a \le 1. \tag{16}$$

Second, as can be easily seen geometrically, the area $A(D - a, D)$ is an increasing function of D for any a. Therefore, if $D_1 \ge D_2$, we have

$$\begin{aligned} P[\zeta(D_1) > a] &= 1 - e^{-MA(D_1-a,D_1)} \\ &\ge 1 - e^{-MA(D_2-a,D_2)} = P[\zeta(D_2) > a]. \end{aligned} \tag{17}$$

Since the remaining distance to the destination cannot increase, if the distance from the origin to the destination is D, then, for each of the above n' hops, the distance between the transmitting node and the final destination must be between 1 and D. It follows that

$$P[\zeta(1) > a] \le P[X_i > a] \le P[\zeta(D) > a], i = 1, \ldots, n'. \tag{18}$$

Therefore, we can obtain a pessimistic bound for the number of hops to reach the destination if we replace the X_is with a sequence of iid random variables whose distribution is that of $\zeta(1)$ and analogously with $\zeta(D)$ to obtain an optimistic bound. Therefore, we have that

$$\frac{D-1}{E[\zeta(D)]} + 1 \le E[n] < \frac{D}{E[\zeta(1)]} + 1, \tag{19}$$

where $E[\zeta(D)]$ is given in (8).

In Figs. 5, 6, and 7, these bounds are compared with the simulation results. It can be seen that, even though the upper bound is fairly loose in general, the lower bound is an excellent approximation. (This is due to the fact that the probability distribution of $\zeta(D)$ quickly converges to that of $\zeta(\infty)$, which is then a much better approximation that $\zeta(1)$.)

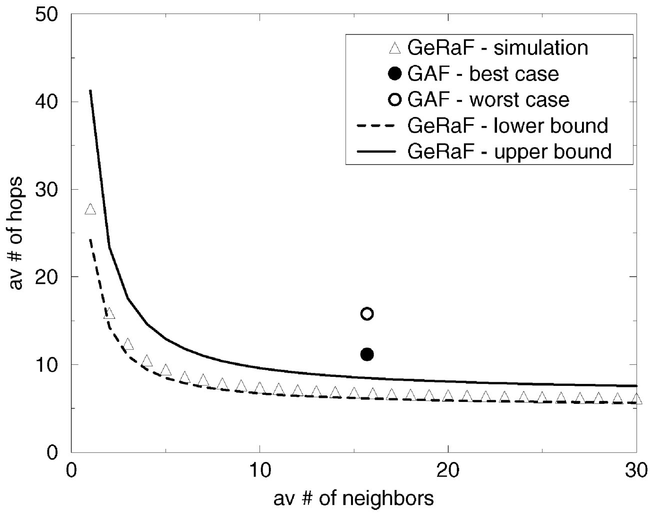

Fig. 5. Average number of hops versus average number of active neighbors. Simulation and analytical bounds. Distance $D = 5$.

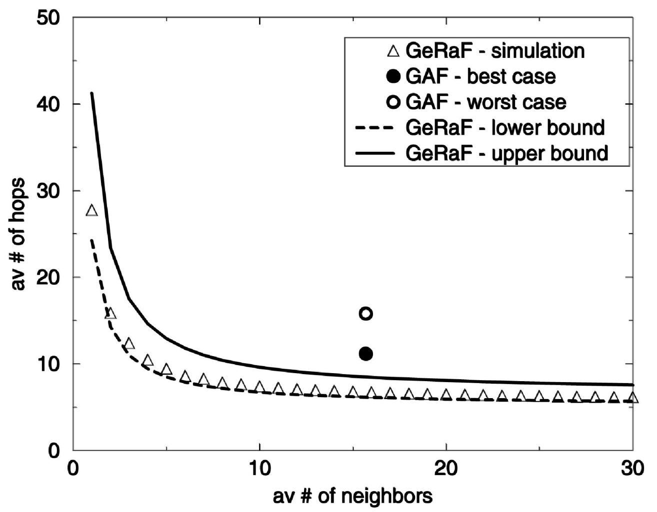

Fig. 6. Average number of hops versus average number of active neighbors. Simulation and analytical bounds. Distance $D = 10$.

3.2 Recursive Evaluation of the Multihop Performance of GeRaF

As another approach which is more accurate but also more computation intensive, we consider here the recursive computation of the average number of hops to reach a destination at distance D.

We quantize the whole range of possible distances from the destination, from 0 through D. Let ν be the number of quantization intervals per unit distance so that the total number of intervals considered is $D\nu$ (for analytical convenience, we assume that D contains an integer number of such quantization intervals). More specifically, let $\Delta_i = \left(\frac{i-1}{\nu}, \frac{i}{\nu}\right]$ be the ith quantization interval.

If the transmitter is within coverage of the final destination, i.e., in $\Delta_i, i = 1, \dots, \nu$, then the number of hops is one. Consider the case in which the transmitter is at distance $\gamma = i/\nu > 1$. The probability that the advancement will lead to a remaining distance in interval $i - \nu + k$ is

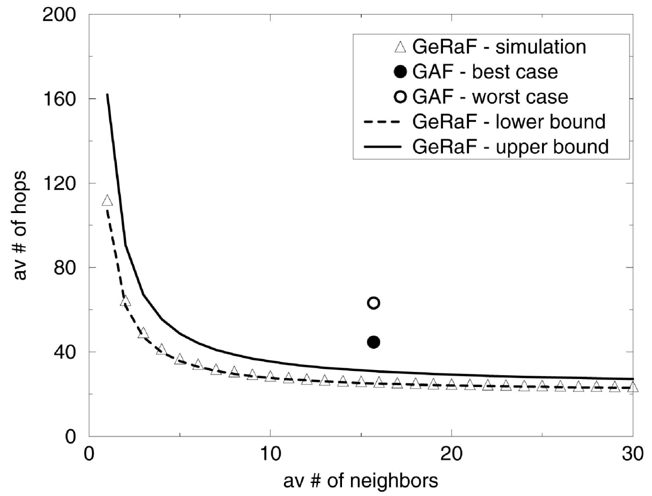

Fig. 7. Average number of hops versus average number of active neighbors. Simulation and analytical bounds. Distance $D = 20$.

$$\omega(i,k) = \begin{cases} e^{-A\left(\frac{i-\nu+k-1}{\nu}, \frac{i}{\nu}\right)} - e^{-A\left(\frac{i-\nu+k}{\nu}, \frac{i}{\nu}\right)} & k = 1, \dots, \nu \\ 0 & \text{otherwise.} \end{cases} \quad (20)$$

In fact, going from $\gamma = i/\nu$ to a point in $\left(\frac{j-1}{\nu}, \frac{j}{\nu}\right]$ corresponds to having no relays with residual distance $\gamma \le \frac{j-1}{\nu}$, but at least one relay with $\gamma \le \frac{j}{\nu}$.

In addition, with probability

$$\omega_0(i) = e^{-A\left(\frac{i}{\nu}, \frac{i}{\nu}\right)}, \quad (21)$$

there is no advancement.

Consider first a pessimistic bound in which, whenever the relay is in interval j, the remaining distance is set to the maximum possible, i.e., j/ν. In this case, we can write the following recursive relationship for the upper bound on the average number of hops, $n_1(i)$, from position i

$$n_1(i) = 1 + \omega_0(i) n_1(i) + \sum_{k=1}^{\nu} \omega(i,k) n_1(i - \nu + k) \quad (22)$$

from which we obtain

$$n_1(i) = \frac{1 + \sum_{k=1}^{\nu-1} \omega(i,k) n_1(i - \nu + k)}{1 - \omega_0(i) - \omega(i,\nu)} \quad (23)$$

with initial condition $n_1(i) = 1, i = 1, \dots, \nu$.

Similarly, we can make the optimistic assumption that, whenever the relay is in interval j, the remaining distance is set to the minimum possible, i.e., $(j-1)/\nu$. In this case, we can write the following recursive relationship for the lower bound on the average number of hops, $n_2(i)$, from position i

$$n_2(i) = 1 + \omega_0(i) n_2(i) + \sum_{k=1}^{\nu} \omega(i,k) n_2(i - \nu + k - 1) \quad (24)$$

from which we obtain

$$n_2(i) = \frac{1 + \sum_{k=1}^{\nu} \omega(i,k) n_2(i - \nu + k - 1)}{1 - \omega_0(i)} \quad (25)$$

with initial condition $n_2(i) = 1, i = 1, \dots, \nu$.

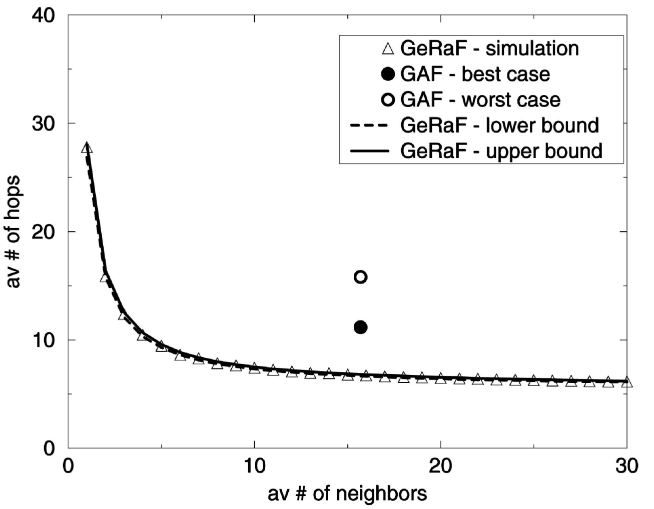

Fig. 8. Average number of hops versus average number of active neighbors. Simulation and analytical bounds (recursion). Distance $D = 5$.

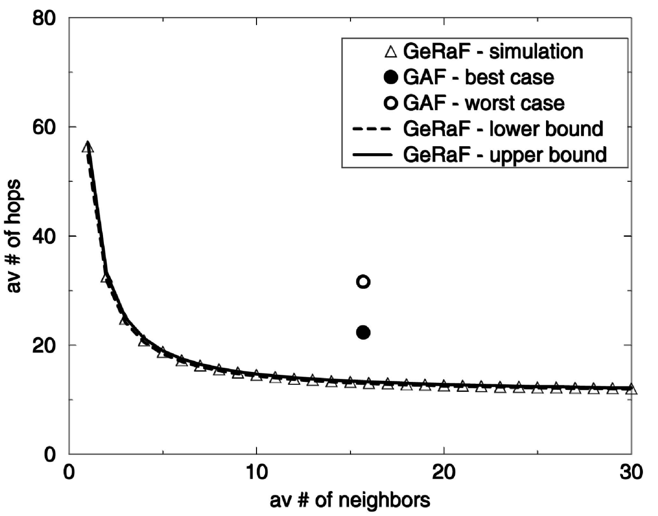

Fig. 9. Average number of hops versus average number of active neighbors. Simulation and analytical bounds (recursion). Distance $D = 10$.

The average number of hops $E[n(D)]$ to reach a destination at distance D (assumed to be equal to an integer number of quantization intervals) can then be bounded as follows:

$$n_2(D\nu) \leq E[n(D)] \leq n_1(D\nu). \tag{26}$$

The tightness of these bounds improves as ν increases and $\lim_{\nu\to\infty} n_1(D\nu) = \lim_{\nu\to\infty} n_2(D\nu) = E[n(D)]$. Figs. 8, 9, and 10 show these bounds for $\nu = 50$, which are almost indistinguishable from each other.

A similar approach can be applied to find the whole probability distribution of the number of hops, where the variable in the recursion is the probability mass function of the number of hops from a given distance to the destination. In this case, if

$$\mu(n, i) = P[n \text{ hops from distance } i/\nu], \tag{27}$$

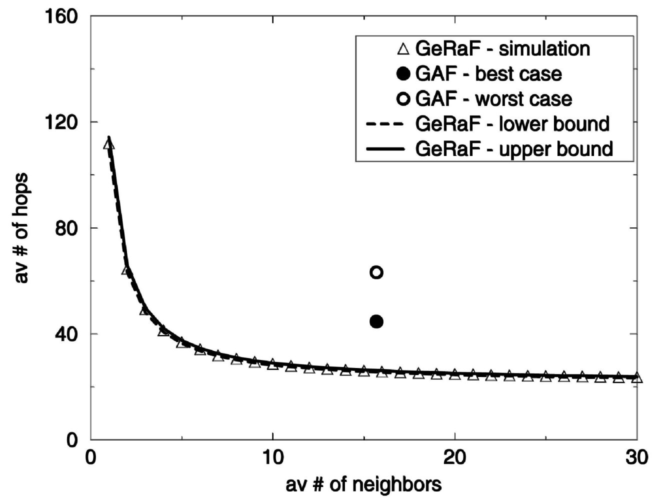

Fig. 10. Average number of hops versus average number of active neighbors. Simulation and analytical bounds (recursion). Distance $D = 20$.

we have the following recursion for the pessimistic bound

$$\mu(n, i) = \frac{\sum_{k=1}^{\nu-1} \omega(i, k)\mu(n-1, i-\nu+k)}{1 - \omega_0(i) - \omega(i, \nu)}, \quad n \geq 1, i = \nu+1, \ldots, \nu d, \tag{28}$$

with initial condition

$$\mu(n, i) = \begin{cases} 1 & n = 1, i = 1, \ldots, \nu \\ 0 & n > 1, i = 1, \ldots, \nu \end{cases} \tag{29}$$

and similarly for the optimistic bound.

4 A Practical Scheme

In a previous section, we have evaluated the statistics of the number of hops which are needed to deliver a packet to the destination. In that simple computation, we assumed that the active neighbor closest to the destination was selected. Here, we propose a simple implementable mechanism to make this selection and show that almost ideal performance can be achieved.

A node which wants to transmit a packet broadcasts a message. All active nodes in its coverage area will hear the message. Each node will then determine its own distance from the final destination and assess its own adequacy as a relay. This is done by first dividing the coverage area in two parts: the relay region, which contains all points closer to the destination than the transmitting node, and the nonrelay region, which contains all other points within range. Nodes in the nonrelay region are never selected as relays.

Further, the relay region is sliced in N_p "priority regions," based on the distance from the destination. More specifically, region $\mathcal{A}_i$ contains all points in the coverage region whose distance from the final destination is $D - 1 + (i-1)/N_p \leq \gamma < D - 1 + i/N_p, i = 1, 2, \ldots, N_p$ (D is the distance from the transmitting node to the final destination and the radius of coverage is normalized to unity).

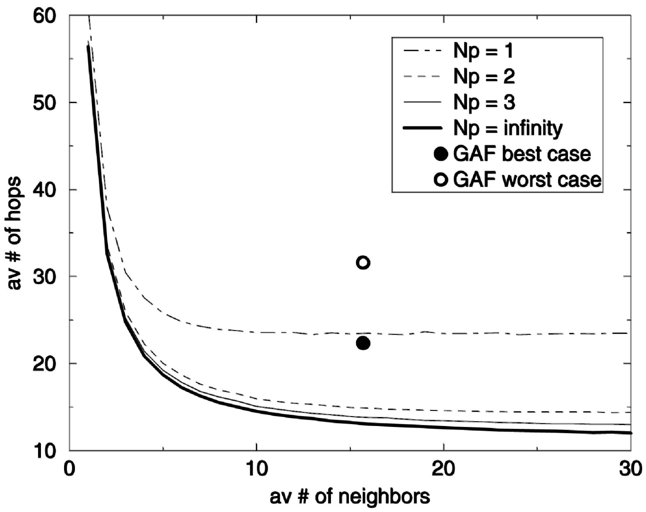

Fig. 11. Average number of hops versus average number of active neighbors for various values of N_p. Distance $D = 10$.

Nodes in $\mathcal{A}_1$, which are those closest to the destination, contend first. If no nodes are found in $\mathcal{A}_1$, then nodes in $\mathcal{A}_2$ contend, and so on until either nodes are found or all regions are empty. In the latter case, one "zero-hop" is counted and the transmitter retries (note that, since nodes wake up randomly, each reattempt will see an independent set of nodes if the reattempt times are appropriately chosen with respect to the on/off activity characteristics of the nodes).

The specific details of the contention scheme are not important for our purposes. An example of a possible scheme is the following: Assume that time is slotted. In the first slot after the transmitter has sent a message, all nodes which received the message and are in $\mathcal{A}_1$ send a reply. If only one reply is generated, the contention successfully terminates. If no reply is generated, then $\mathcal{A}_1$ was empty and the transmitter will send a signaling message which will then trigger all nodes in $\mathcal{A}_2$ to send a reply, etc. If multiple nodes reply simultaneously, the collision can be resolved by means of any collision resolution scheme (e.g., a splitting algorithm). One such algorithm is considered in detail in [1].

Our simulation is therefore organized as follows: The packet starts at the origin node. Within the coverage area, a number of active nodes are randomly placed and subdivided into regions according to their geographical location with respect to the destination. The nonempty region which is closest to the destination is then selected and one of the nodes in it is randomly picked and chosen as the relay. Note, in fact, that if the collision resolution scheme within a priority region does not use geographical information (which, on the other hand, is used in associating nodes to the regions), all nodes in a region are equally likely to win the collision. One hop is counted and everything is repeated, using the relay node as the origin. If the relay node is within range of the destination, the process terminates in one more hop. If all regions are empty, one hop is counted and the origin node is not updated.

The result of this procedure as a function of the number of regions considered is shown in Fig. 11, where the average number of hops is plotted versus the average number of active nodes within coverage. The case $N_p = 1$ corresponds to the fact that any node closer to the destination than the origin will do. This, of course, does not perform well, but, as soon as at least two regions are considered, the performance is close to the case $N_p = \infty$, which corresponds to the idealized scheme presented before. These results show that a simple rule in which each node determines its own region and then contends with all other nodes in that region is essentially as good as the (practically infeasible) ideal selection as long as $N_p \geq 2$. Clearly, the value of N_p and the specific strategy with which contention is resolved will affect the time it takes to transmit a packet and, therefore, is relevant for latency as well as energy consumption [1]. However, since here we are merely interested in hop count, this simple evaluation is adequate.

In order to provide some analytical support to this discussion, consider the following: Let the relay area be divided in N_p slices as defined above and let $M' = M/\pi = d\rho$ be the density of relays per unit area. Also note that the advancement of a packet toward the destination corresponds to the position of a randomly picked node in the nonempty region which has highest priority. Let C_i be the average advancement toward the destination which corresponds to a randomly chosen node in priority region $\mathcal{A}_i$. Then, the average advancement is C_1 if $\mathcal{A}_1$ contains at least one relay, with probability $1 - e^{-M'\mathcal{A}_1}$. In general, the average advancement is C_i if all $\mathcal{A}_j, j = 1, \ldots, i-1$ are empty, whereas $\mathcal{A}_i$ contains at least one relay, with probability $\left(1 - e^{-M'\mathcal{A}_i}\right)\prod_{j=1}^{i-1} e^{-M'\mathcal{A}_j}$. If all regions are empty, with probability $\prod_{j=1}^{N_p} e^{-M'\mathcal{A}_j}$, the advancement is zero. The average advancement in one hop can therefore be evaluated as

$$E[\zeta] = \sum_{i=1}^{N_p} C_i \left(1 - e^{-M'\mathcal{A}_i}\right) \prod_{j=1}^{i-1} e^{-M'\mathcal{A}_j}, \qquad (30)$$

where C_i depends on D and N_p, and can be computed as

$$C_i = D - \frac{2\int_{D-1+\frac{i-1}{N_p}}^{D-1+\frac{i}{N_p}} a^2 \arccos\left(\frac{a^2+D^2-1}{2aD}\right) da}{2\int_{D-1+\frac{i-1}{N_p}}^{D-1+\frac{i}{N_p}} a \arccos\left(\frac{a^2+D^2-1}{2aD}\right) da}. \qquad (31)$$

If $M, M' \to \infty$ (very dense networks), $\mathcal{A}_1$ is never empty, and we obtain

$$E[\zeta] \to C_1. \qquad (32)$$

Table 1 shows the value of C_1 versus N_p and D. It can be clearly seen that, in all cases, the value for $D = \infty$ can be used as a good approximation (except for the somewhat extreme case $N_p = 1, D = 1$, the relative error is less than 5 percent) and, in all cases, it is an optimistic bound. From geometric arguments, we can show that

TABLE 1
Average Advancement for Very Dense Networks, C_1 Versus N_p and D

	$D=1$	$D=2$	$D=5$	$D=10$	$D=\infty$
$N_p=1$	0.3572	0.4013	0.4166	0.4207	0.4244
$N_p=2$	0.6717	0.6979	0.7030	0.7041	0.7050
$N_p=3$	0.7799	0.7987	0.8012	0.8017	0.8021
$N_p=4$	0.8345	0.8491	0.8506	0.8509	0.8512
$N_p=\infty$	1.0000	1.0000	1.0000	1.0000	1.0000

$$\lim_{D\to\infty} C_1 = \frac{\int_x^1 a\sqrt{1-a^2}da}{\int_x^1 \sqrt{1-a^2}da} = \frac{4(1-x^2)^{3/2}}{3(\pi - 2\arcsin x - 2x\sqrt{1-x^2})}, \quad x = 1 - \frac{1}{N_p} \tag{33}$$

so that simple considerations can be made based on close-form expressions.

In the situation in which C_1 weakly depends on D, the average number of hops to the destination can be approximately evaluated as being inversely proportional to C_1 itself (this is actually the asymptotic value for $M \to \infty$). From the table, we see that even a relatively small value of N_p already provides significantly good multihop performance, as was also shown by the simulation results of Fig. 11.[4]

As a final remark, note that the recursive approach of Section 3.2 can still be used to provide bounds by modifying it as follows (suppose, for simplicity, that each priority region corresponds to an integer number K of quantization intervals): The probability of making a transition from a distance $\gamma = i/\nu > 1$ to an interval in the range $i-\nu+(j-1)K+1, \dots, i-\nu+jK$ (i.e., in $\mathcal{A}_j$) is the probability that the first $j-1$ priority regions contain no relays while the jth one is not empty. Given this fact, the probability of choosing a specific interval in this range is proportional to the area of the corresponding slice. Note, in fact, that once we have determined the lowest index nonempty priority region, the winner of the contention will be uniformly distributed within the whole region. More specifically, the transition probabilities are computed as

$$\omega(i,(j-1)K+k) = \begin{cases} P_1(i,j)P_2(i,j,k) & j=1,\dots,N_p, \\ & k=1,\dots,K \\ 0 & \text{otherwise,} \end{cases} \tag{34}$$

where

$$P_1(i,j) = e^{-A\left(\frac{i-\nu+(j-1)K}{\nu},\frac{i}{\nu}\right)} - e^{-A\left(\frac{i-\nu+jK}{\nu},\frac{i}{\nu}\right)} \tag{35}$$

is the probability that the relay is in $\mathcal{A}_j$, and

$$P_2(i,j,k) = \frac{A\left(\frac{i-\nu+(j-1)K+k}{\nu},\frac{i}{\nu}\right) - A\left(\frac{i-\nu+(j-1)K+k-1}{\nu},\frac{i}{\nu}\right)}{A\left(\frac{i-\nu+jK}{\nu},\frac{i}{\nu}\right) - A\left(\frac{i-\nu+(j-1)K+k}{\nu},\frac{i}{\nu}\right)} \tag{36}$$

is the conditional probability that the remaining distance is in the $(i-\nu+(j-1)K+k)\text{th}$ quantization interval given that the relay is in $\mathcal{A}_j$. With these newly defined probabilities, the previous recursions still apply.

5 Discussion and Practical Considerations

So far, we have not discussed how a practical protocol based on this concept can be implemented and how it performs in terms of delay and energy consumption. Also, the impact of imperfect location information, MAC details, localization overheads, node failure, has not been addressed. The main focus of this paper is, in fact, on the basic concept and on the multihop performance. In this section, we briefly address a number of issues which are related to the practical implementation of a protocol based on this idea, as well as other issues which may arise in a practical scenario. For a more complete description of the protocol and of its energy-latency performance, we refer the reader to [1].

The mechanism proposed in [1] is based on collision avoidance. Since sleep modes make it hard to use RTS/CTS handshakes effectively, the use of a busy tone was considered. Each node has two radios (as assumed in [3]) operating on different frequencies. One is used for data exchange, the other to issue busy tones while a node is receiving. When a node wants to send a message, it issues an RTS on a broadcast MAC address. This RTS explicitly contains the location of the transmitter and of the final destination for the message. Nodes who can hear this message will contend to be its relays according to their own location toward the destination. Note, in fact, that, based on the location information for the transmitter and for the final destination and based on the node's knowledge of its own position, the determination of the priority region is a simple geometric calculation.

Based on their own priority, potential relays will respond to the RTS with CTS messages. In the first CTS slot after the RTS, all relays in $\mathcal{A}_1$ will respond. If no CTSs are sent (i.e., $\mathcal{A}_1$ is empty), in the next CTS slot all relays in $\mathcal{A}_2$ send a CTS, etc. When a single CTS is received, the contention phase ends. If multiple CTSs are received, the nodes involved follow a collision resolution algorithm (any of the many existing algorithms can be used). If no relays are present, the transmitting node will retry and, in this case, due to the dynamics of the sleep modes, a different set of potential relays will be available. This mechanism is guaranteed to have a single winner [1]. Once the contention phase is completed, the winner will relay the message by using the same mechanism.

The energy-latency trade off for this protocol is studied in some detail in [1]. As an example of the results that can be obtained, we report in Fig. 12 a plot from [1] which shows the behavior of the energy-latency trade off for GeRaF and for STEM. In the figure, N is the average number of deployed nodes per coverage area (i.e., those active as well as those sleeping) and the curves are generated by varying the sleep-mode duty cycle, d (so that $M = dN$). From the figure, we can see that, for dense networks ($N = 100$), GeRaF can significantly outperform

4. These intuitive arguments could be made more rigorous following the methodology of Section 3.1.

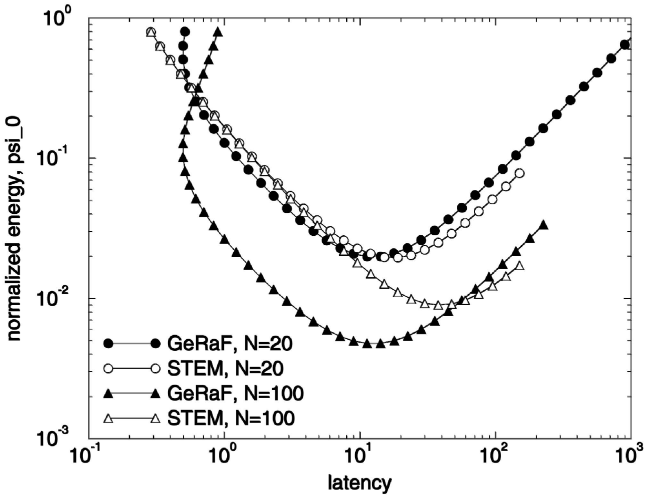

Fig. 12. Average normalized energy consumption, ψ_0, versus latency. GeRaF and STEM compared. $N = 20, 100$, network load 0.01 [1].

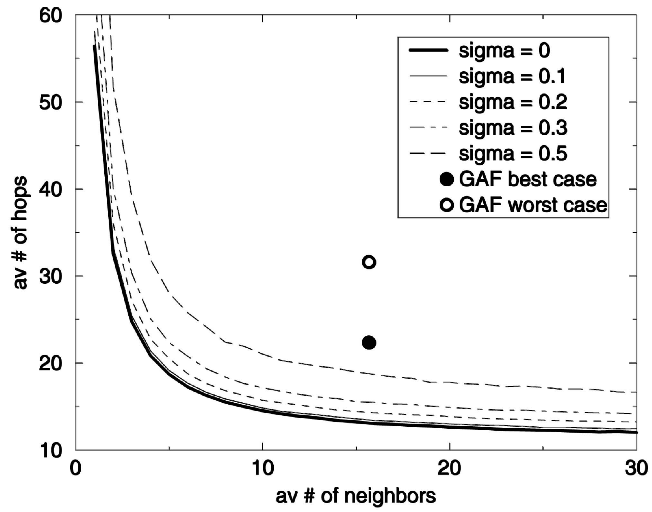

Fig. 13. Average number of hops versus average number of active neighbors. Distance $D = 10$. Gaussian location error with zero mean and standard deviation σ.

STEM and therefore appears as a promising alternative for low-power networking.

An element of complexity of GeRaF is the need for position information. While addressing practical algorithms to obtain such information is out of the scope of the present paper, we note that, in many situations in which sensor nodes are stationary or quasi-stationary, this information could be provided at network set-up time by means of some positioning algorithms. Although the overhead involved will have to be evaluated, its impact is not very significant if this procedure can be done only once initially or repeated infrequently. On the other hand, major benefits of GeRaF are that no routing table maintenance and no coordination among nodes are needed. Notice that the signaling involved in these activities would be needed even in stationary networks since dynamics are caused by sleep modes. On the other hand, in a location-based scheme, the only relevant dynamic is true node mobility. Another issue may relate to the knowledge of the position of the final destination. In many cases, sensed data is transmitted in response to a query or expression of interest, which, in this case, will have to include the geographic address of the sink node.

Also of interest is the effect of erroneous position information. In order to assess the impact of such errors, we have produced results for a scenario in which the selection of the relay nodes is done based on a perturbed version of the actual nodes' locations. More specifically, we introduced Gaussian errors on the coordinates, with zero mean and standard deviation σ. The results of Fig. 13 show that, unless the standard deviation is a substantial fraction of the coverage radius, the performance degradation introduced is modest and that, even with $\sigma = 0.5$, GeRaF still does better than GAF.

Finally, there are some cases in which forwarding directly toward the destination may not be the best choice (e.g., network partition or large obstacles). While a partitioned network is a problem for any forwarding scheme, the case in which direct forwarding leads to a zone in which there are no relays or there is a hole of coverage can be avoided by making the forwarding mechanism a little smarter (at the price of some complexity). For example, if a node tries to forward a packet to a given destination and fails (e.g., no relays ever volunteer because there are no nodes available), it can remember this fact and reject any packets for that destination. This is easily done by just refraining from volunteering whenever the RTS indicates that destination. This has a back-propagation effect which essentially makes the network learn to avoid some "bad" zones or directions. In order to improve this, one could extend the relay area to the whole coverage area (not just the portion which faces the destination), thereby allowing (though only when strictly necessary) the choice of relays which may temporarily increase the distance from the destination (e.g., as may be needed to go around an obstacle [30]).

6 Conclusions and Future Work

In this paper, we have described a novel forwarding technique based on geographical location of the nodes involved and random selection of the relaying node via contention among receivers. We first focused on the multihop performance of such a solution in terms of average number of hops to reach a destination as a function of the distance and of the average number of available neighbors. An idealized scheme (in which the best relay node is always chosen) was discussed and its performance was evaluated by means of both simulation and analytical techniques. A practical scheme to select one of the best relays was shown to achieve performance very close to that of the ideal case.

Many issues remain to be addressed, especially those related to practical implementations and performance implications of the various possible design choices. Even though not the main focus of this paper, some of these issues have been qualitatively discussed, while more details can be found in [1], which gives the description of a detailed MAC protocol based on the concepts discussed here, as well as the evaluation of the energy and latency performance.

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