On the performance of geographical routing in the presence of localization errors

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Abstract— **In this paper, a detailed study of the performance of geographic routing protocols in the presence of localization errors is carried out. Both analytical and simulation results illustrate the major impact of localization errors on the protocol goodput and route discovery energy. The performance metrics observed were the packet delivery ratio and the power consumed at a node for routing. It is shown that significant performance deterioration occurs with location errors as low as 20% of a node's radio range with no other obstacles in the network. To counteract this degradation, an enhancement is proposed that increases the error tolerance to about 40% radio range and in addition improves the performance consistently for any location error. Furthermore, the effect of obstacles in conjuction with location errors on the routing performance is also investigated.**

I. INTRODUCTION

Geographical routing ([1], [2], [3], [4]) has become a widely accepted class of routing protocols in ad hoc networks. The distinguishing characteristic of this class of protocols is the use of node location information to route packets geographically towards the destination. One of the biggest advantages of geographic routing is the small overhead - almost no routing tables are required apart from a list of neighbors and their positions. This translates to very efficient scaling as the network size grows large. Geographical routing also eliminates the route setup phase in most cases, reducing communication overhead and setup time.

This combination of features makes geographical routing especially attractive for sensor networks. Node location information is necessary for many applications of sensor networks; sensed data is almost always useless unless accompanied by some positional information. Thus some localization mechanism is included in every sensor network (e.g. GPS, [5], [6], [7], [8]), and geographic routing imposes no additional requirement in that regard.

The commonality between all geographic protocol variants is the usage of greedy forwarding till the packet reaches an obstacle or void, at which point they differ in the mechanisms they use to route around those obstacles. Different performance studies of geographical routing usually compare these options. It is interesting that almost all performance investigations have assumed - explicitly or implicitly - the availability of perfectly accurate position information. In reality, however, the position information always has some error - reasons can be either inaccurate range measurements, algorithmic artifacts or a combination of both. These errors (which can be on the order of a node's radio range [6] [8]) can potentially affect the packet delivery ratio (goodput) and energy performance of geographical routing.

Unfortunately, this effect has usually been neglected while studying the performance of geographic routing. Notable exceptions are the recent work by Seada et. al. ([9]) where they focus on the performance of GPSR [3] and by He et. al. ([10]) where they evaluate a hierarchical geographic protocol proposed in [11]. In this paper, we use both analysis and simulation to understand the effect of localization error on geographic routing in general and propose a simple mechanism to reduce this performance deterioration. More precisely, we make the following three contributions.

The first contribution is to provide a detailed study (analysis and simulation) of the effect of localization error on the common part of all geographic routing schemes - greedy forwarding. This provides a baseline for the performance of all geographic routing schemes. Furthermore, we focus on the performance (simulation only) of the protocol proposed in [4] which uses flooding as a mechanism to route around voids.

The second contribution is a proposed method to reduce the performance deterioration with location error. This involves the usage of second order neighborhood information (where available). Second order neighbors are defined as the neighbors of neighbors, and information about them is sometimes maintained in MAC layer implementations ([12], [13]).

The third and final contribution is in understanding the effects of localization error when obstacles are present. It is hoped that these three aspects of the paper provide a better understanding of the performance of geographic routing protocols in real-world deployments and scenarios. It also serves as a useful guide for the localization accuracies and node densities needed to achieve reasonable routing performance.

The paper is organized as follows. Section II presents some background work in this area. This is followed by a description of the protocols and the localization error model in Sections III and IV and analysis of greedy forwarding in Section V. Simulation setup and results are discussed in Section VI, with the paper concluding in Section VII.

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II. RELATED WORK

One of the earliest papers about geographical routing was [1]. In that work, the idea of using node locations to forward packets towards the destination was proposed. It also used flooding as a method for routing around outages in a network. The flood was limited by the maximum diameter of the outage; if the size of the outage was not known, then a suitable value was chosen. Subsequent work in geographic routing maintained the notion of greedy forwarding, but focused on other solutions for routing around voids and obstacles.

GPSR ([3]) is one of the well-known geographic routing schemes that proposed using perimeter or face routing to route around voids or obstacles when greedy forwarding fails. When a packet is stuck at a void or obstacle, face routing is used to route around dead-ends until nodes closer to the destination are found. Recently, GHT ([14]) was proposed specifically for sensor networks, and uses a geographic hash table system to store the key-value pair at the sensor node closest to the hash of the key. GPSR is used as an underlying mechanism to route to the hash location.

Another related work is LAR proposed in [2] where they try to take mobility of nodes into account by defining a request zone within which all nodes are flooded and used for forwarding. This request zone is a box defined by the current node and the expected region (depending on the node's mobility pattern) of the destination node. Finally, [4] proposed another variant of geographical routing very similar to [1] where flooding is used as a mechanism to route around voids. Compared to perimeter routing techniques, the advantage of flooding is that the protocol will definitely find a path between source and destination if they are connected. However, there is a higher energy cost with this mechanism.

[15] is a proposal to use geographic routing where no location information is available. Logical coordinates are assigned over time based upon knowledge about connectivity which is obtained using global floods. This is a very good technique when localization methods are not possible, but it is not very efficient as compared to geographical routing when location information is used. In addition, there is no mechanism to route around voids or dead-ends.

Recently, there have been two papers that address the issue of location errors and their impact on geographic routing. In [10], He et. al. show the performance of geographical routing as suggested in [11] in the presence of some localization error (in addition to proposing a localization scheme). However, the protocol in [11] is hierarchical in nature and does not consider any mechanism to route around voids and obstacles. On the other hand, Seada et. al. ([9]) do a fairly detailed study of face routing algorithms (specifically GPSR and GHT) and show certain pathological cases that can affect the routing performance. They also propose a fix that improves the performance substantially[1]. In contrast to these papers, we consider geographic routing with flooding as a mechanism to route around obstacles. Additionally, we consider the case of obstacles in the network and combine its effect with localization errors to evaluate the performance of the protocol.

III. PROTOCOL DESCRIPTIONS

We will now describe the protocols considered in the paper. The **basic** protocol follows the scheme described in [4] without the flooding mechanism. When a node has to forward a packet, it selects a neighboring node that is closest to the destination node to be the next hop. In case the current node does not have any neighbor that is closer to the destination, then the packet is considered to be *stuck*. This situation may occur either due to the node encountering an obstacle or void in the network. In the basic protocol, such stuck packets are dropped since the node does not have a next hop node.

The **flooding** protocol is the full scheme of [4], which means that it has the capability of routing a packet when it gets stuck. Here once a packet gets stuck, the node floods all its neighbors trying to find a route to the destination. This flooding continues till the destination node is discovered. Hence the flooding protocol will discover a route to the destination despite the presence of voids or obstacles, however, there is a high penalty in terms of power consumption.

Second order routing is an enhancement to geographic routing that requires all nodes to have knowledge of their second order neighbors (neighbors of neighbors) and their positions. This information may not always be available, but in certain cases, nodes may have it due to other requirements such as certain distributed algorithms for tasks such as channel selection and local MAC ID distribution which require nodes to have unique values within a two hop neighborhood ([12], [13]). This information is then used while selecting the next hop node. Similar to basic geographic routing, the neighbor furthest towards the destination is chosen as the next hop node. But there is one other criteria the selected node should satisfy, and that is it should have a neighboring node that is still closer to the destination. If the node does not satisfy this criterion, then it is not selected as the next hop node, and the next closest neighbor to the destination is tried. This continues till a neighbor that satisfies this criterion is found.

The advantage of using this check is that it ensures that the packet does not get stuck at the next hop, reducing the chances of hitting an obstacle or a void. It is also possible that the neighboring node may have calculated its position erroneously, and may not be the best node for routing to the destination, or may actually not even provide a progress at all; using second order information reduces the probability of that case also. Effectively, this mechanism increases the distance a node can *look ahead* towards the destination, so as to improve the accuracy of geographical routing. Similar to standard geographic routing, second order routing could also use flooding as a mechanism to route packets when they get stuck.

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[1] It is interesting to note that the fix they propose requires two neighboring nodes to exchange information about their neighbors. This is akin to knowing the second order neighborhood information in our case.

IV. LOCALIZATION ERROR MODEL

As mentioned earlier, there are many localization schemes suggested in the literature (GPS, [5], [6], [7], [8]), each having different performance and error characteristics. Hence for simplicity and to get a generic idea of the effect of localization errors, we consider a very simple localization error model in this paper.

We assume that the locationing algorithm has an error characteristic that is circularly symmetric, i.e., the locationing algorithm would localize a node anywhere within a disk around its actual position (all points within the disk being equiprobable). The radius of the disk characterizes the error and this is done in terms of the radio range of the node. As shown in [6] and [8], the error could be as high as the radio range, thus we will consider localization errors up to a radio range in this paper. Additionally, all nodes have completely independent errors. While this may be different from error characteristics of many distributed locationing schemes, it is fairly accurate for a GPS-based locationing method.

V. ANALYSIS

In the analysis, we only consider the basic protocol described above. This gives us the fundamental packet delivery ratio of all geographic routing protocols since this part of the protocol is common for all of them. Analyzing the performance of the subsequent part of the protocol that tries to route "stuck" packets is hard and is specific to a particular protocol, hence this paper does not consider it for analysis.

A quantity that will be frequently used in the analysis is the area of the lens formed by the intersection of two circles. Given two circles of radius r and R with the centers separated by a distance d, the area of the lens is given by [16],

$$\begin{aligned}\Psi(r,R,d) &= \\ r^2\cos^{-1}&\left(\frac{d^2+r^2-R^2}{2dr}\right)+R^2\cos^{-1}\left(\frac{d^2+R^2-r^2}{2dR}\right)\\ &-\frac{\sqrt{(-d+r+R)(d+r-R)(d-r+R)(d+r+R)}}{2}\end{aligned} \tag{1}$$

A. Geographical routing using first order neighbors only

Let us first consider the case of geographic routing where each node only has information about its neighbors. We want to understand the packet delivery ratio as the location error increases. Assume that nodes are uniformly and randomly distributed with density ρ nodes/sq. m.

Now, a packet is delivered successfully to the destination if it does not get stuck anywhere. When the position error is zero, this implies that every node along the route should have at least one neighbor that is closer than itself to the destination. The first hop forwarding region of a node ($\mathcal{R}_1$) is defined as the region in space that is within radio range of the node and closer to the destination than the current node. If the area of the first hop forwarding region is given by $\Phi_1(0, D)$ (the subscript 1 refers to the use of only the first order neighbors, 0 refers to zero position error and D is the distance to the destination from the current node), then the probability of a node having a neighbor closer to the destination when there is no location error is given by $(1 - e^{-\rho\Phi_1(0,D)})$. Note that $\Phi_1(0, D) = \Psi(R_{max}, D, D)$. Here, R_{max} is the radio range of a node. Hence the end-to-end packet delivery ratio (PDR) for a path length of N_{hops} is,

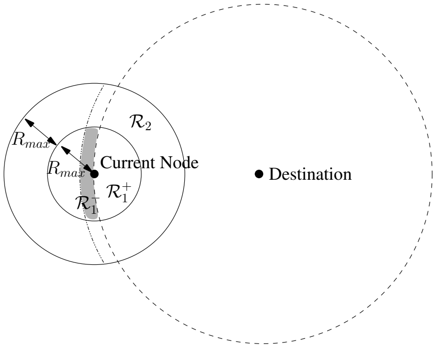

Fig. 1. Greedy forwarding in the presence of localization errors

$$\text{PDR} \approx \prod_{i=1}^{N_{hops}} \left(1 - e^{-\rho\Phi_1(0, \frac{D\cdot i}{N_{hops}})}\right) \tag{2}$$

Note that the forwarding region is largest when the destination is infinitely far off, and gets progressively smaller as the node is closer to the destination. Let us now consider the case of a network where the position error is κ. In that case, while selecting the next hop, two cases can occur:

- Nodes that are actually within the first hop forwarding region believe that they are outside and hence do not forward the packet
- Nodes that are actually outside the first hop forwarding region believe that they are inside the region and try to forward the packet

We account for the first set of nodes by changing the effective area of the first hop forwarding region. Hence, the new area is given by,

$$\int\limits_{\overline{x}\in\mathcal{R}_1^+} Pr\{\overline{x} \text{ localized within the forwarding region}\}d\overline{x}$$

Here $\overline{x}$ is the coordinates of the node position. The region $\mathcal{R}_1^+$ is the region in space that provides positive progress towards the destination and is shown in Fig. 1. The probability of being localized within the first hop forwarding region is given by:

$$Pr\{\overline{x} \text{ localized within the forwarding region}\} = \frac{\Psi(\kappa R_{max}, D, \|\overline{x}\|)}{\pi(\kappa R_{max})^2}$$

This result is just a numerical computation. The numerator is the area of intersection of two circles. The first one being the circle formed with the destination as the center and radius equal to the distance between the destination and the current node. The second circle is the location error circle. The distance between the centers of the two circles is the distance between the destination and the point in the forwarding region. The denominator is the area of the location error circle.

On the other hand, the nodes in the second case (shown as the region $\mathcal{R}_1^-$ in Fig. 1) should not be forwarding packets, hence that accounts for a reduction in the effective forwarding area in the expression. Hence,

$$\Phi_1(\kappa, D) = \int\limits_{\overline{x}\in\mathcal{R}_1^+} \frac{\Psi(\kappa R_{max}, D, \|\overline{x}\|)}{\pi(\kappa R_{max})^2} d\overline{x} - \int\limits_{\overline{x}\in\mathcal{R}_1^-} \frac{\Psi(\kappa R_{max}, D, \|\overline{x}\|)}{\pi(\kappa R_{max})^2} d\overline{x} \quad (3)$$

B. Geographical routing using second order neighborhood information

For the analysis of the case of geographic routing using second order neighborhood information, let us call the region of space that is closer to the destination than the current node and more than one but less than twice the radio range away, as the second hop forwarding region (shown as $\mathcal{R}_2$ in Fig. 1). Here, a node forwards packets to a neighbor only when it in turn has another neighbor that is still closer to the destination. Thus when a node receives a packet, it already knows that there is at least one node in its first hop forwarding region. Hence,

$$Pr\{N \text{ nodes in first hop}|1 \text{ node already there}\} = \frac{(\rho\Phi_1(\kappa, D))^{N-1}}{(N-1)!} e^{-\rho\Phi_1(\kappa,D)}$$

Now, a packet is forwarded if:

- One or more nodes are present in the second hop forwarding region that have connectivity to a node in the first hop region
- There are at least two nodes in the first hop region (we already have one) that have connectivity to each other

Now, for a node at position $\overline{x}$ in the second hop forwarding region, given that there are N nodes in the first hop region, the probability of connectivity to a node in the first hop forwarding region is given by,

$$Pr\{\overline{x} \text{ is connected}|N \text{ nodes in first hop}\} = 1 - \left(1 - \frac{\phi_1(\overline{x})}{\Phi_1(\kappa, D)}\right)^N \quad (4)$$

Here, $\phi_1(\overline{x})$ is the area of the first hop region that is within radio range of the node in the second hop forwarding region. $\Phi_1(\kappa, D)$ is the total area of the first hop forwarding region. Thus, the area of the second hop forwarding region is,

$$\begin{aligned}
&\Phi_2(\kappa, D) \\
&= \sum_{N=1}^{\infty} \int\limits_{\overline{x}\in\mathcal{R}_2} Pr\{\overline{x} \text{ is connected}|N \text{ nodes in } 1^{st} \text{ hop}\} \\
&\quad \cdot Pr\{N \text{ nodes in } 1^{st} \text{ hop}|1 \text{ node already there}\} d\overline{x} \\
&= \sum_{N=1}^{\infty} \int\limits_{\overline{x}\in\mathcal{R}_2} \left[1 - \left(1 - \frac{\phi_1(\overline{x})}{\Phi_1(\kappa, D)}\right)^N\right] \\
&\quad \cdot \frac{(\rho\Phi_1(\kappa, D))^{N-1}}{(N-1)!} e^{-\rho\Phi_1(\kappa,D)} d\overline{x} \\
&= \int\limits_{\overline{x}\in\mathcal{R}_2} \left[1 - \left(1 - \frac{\phi_1(\overline{x})}{\Phi_1(\kappa, D)}\right) e^{-\rho\phi_1(\overline{x})}\right] d\overline{x} \quad (5)
\end{aligned}$$

The last step was by interchanging summation and integration.

Similarly, we can consider the second case above, i.e., multiple nodes in the first hop forwarding region that have connectivity to each other. So similar to above,

$$\begin{aligned}
&\Phi_1(\kappa, D) \\
&= \sum_{N=1}^{\infty} \int\limits_{\overline{x}\in\mathcal{R}_1} Pr\{\overline{x} \text{ is connected}|N \text{ nodes in } 1^{st} \text{ hop}\} \\
&\quad \cdot Pr\{N \text{ nodes in } 1^{st} \text{ hop}|1 \text{ node already there}\} d\overline{x} \\
&= \sum_{N=1}^{\infty} \int\limits_{\overline{x}\in\mathcal{R}_1} \left[1 - \left(1 - \frac{\phi_1(\overline{x})}{\Phi_1(\kappa, D)}\right)^N\right] \\
&\quad \cdot \frac{(\rho\Phi_1(\kappa, D))^{N-1}}{(N-1)!} e^{-\rho\Phi_1(\kappa,D)} d\overline{x} \\
&= \int\limits_{\overline{x}\in\mathcal{R}_1} \left(1 - e^{-\rho\phi_1(\overline{x})}\right) d\overline{x} \quad (6)
\end{aligned}$$

Hence we can put it all together so that the percentage of the end-to-end packet delivery ratio for location error of κ when second order routing is used is given by,

$$\text{PDR} \approx \prod_{i=1}^{N_{hops}} \left(1 - e^{-\rho[\Phi_1(\kappa, \frac{D \cdot i}{N_{hops}}) + \Phi_2(\kappa, \frac{D \cdot i}{N_{hops}})]}\right) \quad (7)$$

VI. SIMULATIONS

To better understand the impact of various parameters on routing performance, a detailed simulation study was carried out in Omnet++ [17]. Since we were mostly interested in the routing performance, MAC layer effects such as collision and interference were not modeled. However, the power required for transmission ($1.8mW$) and reception ($0.6mW$) was taken into account to evaluate the total cost of the protocol. The size of the network was kept constant at 100m × 100m while varying the number of nodes in the simulations. Each node had a radio range of 10m with a radial disk model of connectivity. Nodes were uniformly and randomly placed within the network, and the results were computed as the average of 50 runs. For all simulation runs, packets were

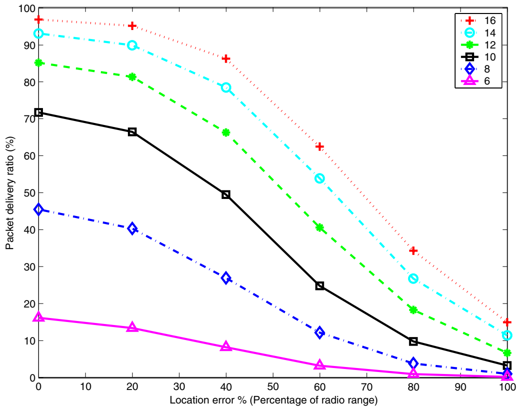

Fig. 2. Packet delivery with position error for the basic protocol with no second order routing. Each curve shows the results for a different average number of neighbors per node.

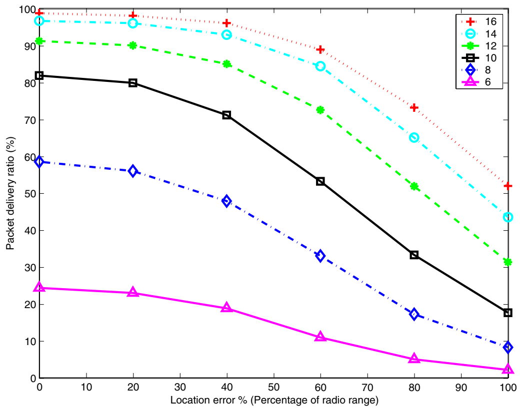

Fig. 3. Packet delivery with position error for the basic protocol with second order routing. Each curve shows the results for a different average number of neighbors per node.

generated at all nodes for every other node in the network that was at least 70m away.

The study was carried out for both the basic and flooding protocols. In addition, both these protocols were augmented by second order neighborhood routing to see its benefit. The cost of obtaining the second order information was considered to be zero, assuming that this information is available at the node due to some other requirements as discussed in Section III. Also, networks with and without obstacles were considered.

The metric used are the packet delivery ratio and the power consumed per node while discovering routes between nodes. It can be argued that the cost of discovering a route is not important over the entire lifetime that a route is used, which may be true if the connection is very long-lived. However, geographical routing is useful where the connection time is short, otherwise a very good case can be made for using a protocol [18] that can optimize the route to ensure minimum energy consumption, maximum network lifetime or any other metric of choice.

A. *No obstacles*

Fig. 2 shows the packet delivery ratio as the location error increases for the basic routing protocol without second order routing. Each curve is for a different node density so that the average number of neighbors per node varies between 6 to 16. As can be seen, the goodput decreases quite rapidly as the location error increases, especially beyond 20% location error.

Fig. 3 plots the same metrics as the previous curve, but shows the results for the basic protocol with second order routing enabled. As can be seen, second order routing improves the goodput by about $5-10\%$ when there is no location error. But more importantly, it reduces the performance degradation with increase in location error, increasing the tolerance of the routing protocol to $\sim 40\%$ location error.

Fig. 4 again shows the packet delivery ratio for the basic routing protocol compared with the theoretical calculation as the density of nodes in the network changes. This is shown for two different values of location errors. Both the cases of with and without second order routing are shown with the lines corresponding to analysis and the points to simulation results.

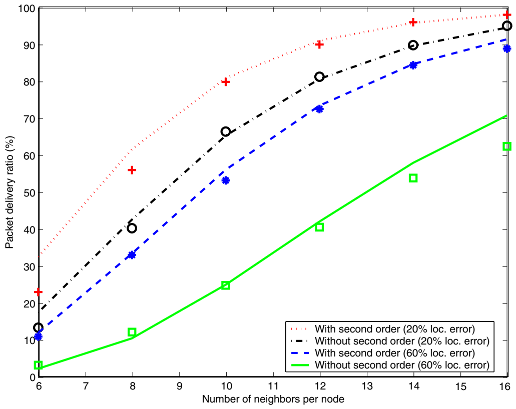

Fig. 4. Packet delivery for the basic protocol with and without second order routing as the number of neighbors per node changes. The results are shown for two different values of location error. The lines are analytical results while the points are obtained from simulation.

It is important to note that since the node positions were generated at random, full connectivity across the network cannot be guaranteed. However, if a path between source and destination exists, the flooding protocol would be able find it and hence the goodput results (Table I) provide an idea of connectivity in a random network with different node densities. The difference between these values and the goodput values for the basic protocol (with and without second order routing) show the percentage of packets that need to resort to flooding to find a path to the destination.

While second order routing increases the packet delivery ratio, it provides another advantage of reducing the power consumption in the network also. This can be seen in Fig. 5 where the plot shows the power consumption per node for two node densities of 8 and 12 neighbors per node. Geographical routing with flooding is considered here, both with and without the second order routing enhancement. The number of packets

TABLE I

GOODPUT OF THE FLOODING PROTOCOL FOR DIFFERENT NODE DENSITIES

Avg. number of neighbors	Routing protocol goodput
6	73.8%
8	95.3%
10	99.1%
12	99.6%
14	99.8%
16	99.8%

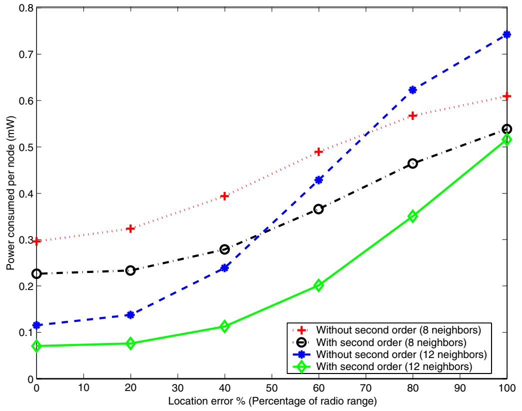

Fig. 5. Power consumed per node for the flooding protocol with change in location error. Both the cases of with and without second order routing are shown for two different values of node density.

generated in the network for both cases of node densities are the same. Hence, as expected, when there is no location error, the power consumption per node is higher for the case of 8 neighbors per node than the denser network. In addition, we can see that using second order routing saves a significant amount of power ($\sim$ 40%) for both the node densities. However, the results are more interesting when location error increases. As can be seen from the plot, beyond a point, the power consumption of the denser network increases beyond the less dense network. While this seems counter-intuitive, it can be explained by the large fraction of packets resorting to flooding as the localization error increases, since packets get stuck even in the denser network. This flooding leads to higher power being consumed in the denser network since a node hears much more traffic within its neighborhood. This is despite the fact that during flooding, a node only forwards the flood once, suppressing any duplicates it sees. But with the denser network, each node receives a larger number of packets (due to larger number of neighbors), and even though it does not transmit more packets than the less dense network, it consumes a lot of energy in reception. This leads to an overall higher energy consumption than less dense networks. This is where second order routing really helps since it reduces the number of floods necessary, hence reducing the power consumption substantially as the location error increases.

Finally, Table II provides a brief look at the average number of hops per connection for the flooding protocol without and enhanced with second order routing. This would give an indication of the average power consumed in the network after the route discovery phase is over. Second order routing provides a fair bit of improvement, especially in dense networks and for high location error.

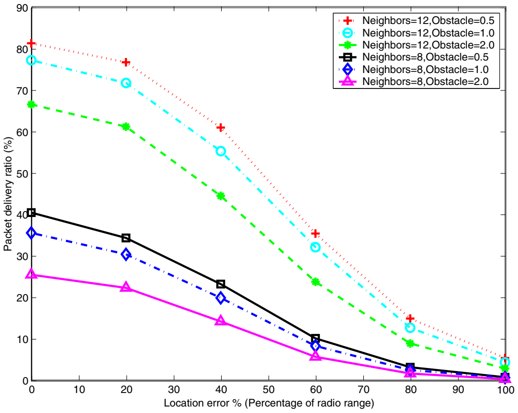

Fig. 6. Packet delivery with position error for the basic protocol with no second order routing. Each curve shows the results for a different average number of neighbors per node and size of the obstacle (as a multiple of the radio range).

TABLE II

AVERAGE NUMBER OF HOPS FOR THE FLOODING GEOGRAPHIC PROTOCOL WITH AND WITHOUT SECOND ORDER ROUTING

Location error	Routing protocols	
	Without 2^{nd} order	With 2^{nd} order
	Avg. number of neighbors $= 8$	
0%	16.46	15.62
40%	17.47	16.40
60%	17.98	17.00
100%	18.50	18.04
	Avg. number of neighbors $= 12$	
0%	12.79	12.36
40%	14.35	13.29
60%	15.82	14.29
100%	17.74	16.29

B. With obstacles

To simulate obstacles in the network, we considered a wall in the middle of the network. The length of the wall was varied as 0.5, 1.0 and 2.0 times the radio range of nodes. The wall was perfectly opaque so that no radio communication was possible across the wall. The traffic pattern was the same as in the case with no obstacles. Fig. 6 shows the goodput of the basic routing protocol without second order routing. The results for two different node densities of 8 and 12 neighbors per node are shown. A similar curve for the basic routing protocol with second order routing is shown in Fig. 7. As would be expected, second order routing suffered a smaller drop in goodput, due to the advantage of being able to “look-ahead” while routing.

Finally, Fig. 8 shows the power consumed per node for the three obstacle sizes and a node density of 8 neighbors. The power saving due to second order routing remained around $30-40\%$. An interesting thing to note in this plot was that for

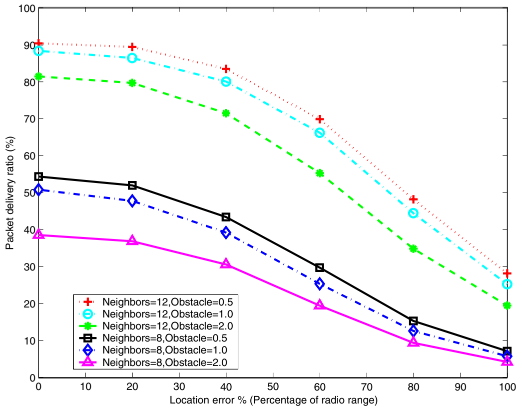

Fig. 7. Packet delivery with position error for the basic protocol with second order routing. Each curve shows the results for a different average number of neighbors per node and size of the obstacle (as a multiple of the radio range).

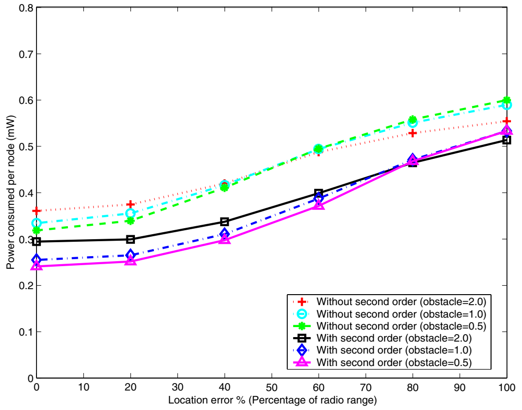

Fig. 8. Power consumed per node for the flooding protocol with change in location error. Both the cases of with and without second order routing are shown for three different obstacle sizes (as a multiple of the radio range) with 8 neighbors per node on average.

high location errors, the power consumption for large obstacles was lower than for the smaller obstacles! This can again be explained by the nature of flooding. For high location errors, almost all the packets had to resort to flooding to find a route, and hence, similar to the case with no obstacles, the receive power dominated. However, a larger obstacle size meant fewer number of nodes actually being within radio range. This reduced the power wasted on receiving the broadcast flood packets and hence the overall power consumption.

VII. CONCLUSIONS AND FUTURE WORK

In this paper, we showed the effect of localization errors on the performance of greedy forwarding and a geographic routing protocol that uses flooding to route around obstacles. Our results indicate that the goodput and energy consumption performance in the network deteriorates considerably for localization errors of more than 20% radio range. Usage of the second hop neighborhood information was shown to mitigate this and increase the tolerance to about 40% error.

Flooding was seen to consume a major portion of the route discovery energy, hence trying to maximize the goodput of greedy forwarding is a good idea. In that regard, GPSR might perform better in terms of energy consumption since it does not need to flood to route around obstacles. However, there is a cost associated with the graph planarization procedure; that comparison is left as future work. Also, GPSR (with the fix suggested in [9]) cannot guarantee delivery of packets even if a path exists when the location error is high; this is an advantage of flooding based geographic protocols.

Obstacles further reduce packet delivery rates and increase the power consumption at the nodes. The heavy cost of flooding to route around obstacles also showed that increasing node density does not necessarily help in reducing power consumption and in fact, when the protocol goodput is low, may actually compound the problem. In such cases, techniques to *quench* a flood may be necessary. It was interesting that larger obstacle sizes indirectly quenched the flood and hence reduced power consumption.

Finally, the paper considered only symmetric and independent location error models. Depending on the localization scheme used, different error characteristics are possible - the impact of such errors is also left for future work.

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