Power-aware Recovery for Geographic Routing

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***Abstract*— Maintaining low power consumption is critical in wireless ad hoc and sensor networks. With packet transmissions and re-transmissions consuming much of the energy resources in wireless networks, it becomes important to minimize the number of transmissions associated with the end-to-end delivery of packets. Power-aware routing algorithms must balance the advantages and disadvantages of selecting to forward packets over shorter high-quality links against selecting longer and less reliable links.**

This paper proposes a new power-aware geographic routing technique that combines geographic greedy routing with probabilistic random walks to recover from local minima (i.e., cases when the forwarding node is not aware of any neighboring node providing "greedy" progress towards the destination). Building upon previous power-aware protocols without recovery mechanisms, our protocol uses simple distance metrics that combine information about the individual reception rates between node pairs and the relative forward progress candidate nodes provide towards the target destination. The combined metrics are used to make greedy choices (when at least one node provides progress) and probabilistic choices (when the packet recovers from a local minimum). Using simulations we show that power-aware routing significantly reduces the energy consumption in the network, and our probabilistic recovery mechanism can significantly increase the delivery rates with only a small decrease in energy efficiency.

I. Introduction

Wireless ad hoc networks consist of geographically distributed nodes, which use wireless communication links to deliver information between nodes. Each node functions as both a host and a router, and the network topology may change dynamically due to node mobility, node failure/recovery, and various physical properties related to the propagation channel (e.g., obstructions, noise, and power limitations).

In multi-hop wireless networks, nodes must cooperate and relay each other's packets toward their final destinations. *Geographic routing* [1]–[4] is attractive for large multi-hop wireless networks in which individual nodes are not typically reliable and/or the network topology frequently changes. Using information about the geographic location of nodes (obtained using a combination of GPS devices and localization systems [5], [6], for example) these protocols allow each node to determine the next node to forward the packet.

In the simplest form of geographic routing, called *greedy routing*, each node forwards the packet to the node within transmission range that is closest to the destination [2]. Many measures of progress have been proposed [2], [7]–[10]. While greedy forwarding is efficient in dense networks, it may fail to find a path in the presence of dead areas, voids, or obstacles. In such networks, a packet may reach a "local minimum" at which point no progress towards the destination is possible. Recovery mechanisms, such as face routing [3], [4] and limited flooding [2], [11], can be used to circumvent and recover from local minima. Both these techniques can guarantee delivery under certain conditions. With face routing, packets are forwarded around the faces of a planar graph (created by removing edges from the neighbor graph).

Wireless links are often unreliable, and can have significantly different reception rates. Energy-efficient greedy routing protocols must therefore efficiently balance the advantages and disadvantages of selecting shorter high-quality links against selecting longer and potentially less reliable links, which provide additional progress towards the final destination.

Our main contribution in this paper is to combine ideas from power-aware greedy protocols and random walk theory to provide a totally distributed routing protocol. The new protocol uses power-aware probabilistic random walks to bypass and recover from local minima. In contrast to face routing protocols, our probabilistic best-effort[1] recovery mechanism does not require any graph structure to be maintained.

Both the greedy and recovery component of our protocol use a distance metric which combines (i) a power-aware metric that estimates the reception rates between individual node pairs [12], and (ii) a progress metric measuring the relative progress candidate nodes make towards the final destination. In greedy mode the packets are forwarded to the neighbor with the largest value; in recovery mode packets are probabilistically forwarded based on the values of individual nodes.

The remainder of the paper is organized as follows. Section II provides a brief overview of related work. Section III defines our routing algorithm. Section IV presents simulation results. Finally, conclusions are presented in Section V.

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[1] While random walk theory ensures that (time-to-live and re-transmission) parameters can be selected to guarantee that packets are eventually delivered in connected networks, we focus on parameter settings for which our protocol is a best-effort protocol. It should be noted, however, that our simulation results show that significant improvements in delivery rates can be achieved by allowing longer random walks, at a very small reduction in energy efficiency.

II. Background

Geographic routing algorithms typically require each forwarding node to know the location of itself, its neighbors, and the destination node. Nodes can easily obtain their own location (using a GPS device, for example), and the location of their neighbors. In addition, many scalable protocols have been proposed that distribute information of the location of the destination (e.g., [5], [6]).

A. Greedy Geographic Routing

The main component of most geographic routing techniques is typically a greedy forwarding mechanism. Greedy routing protocols have been defined based on distances, progress, and/or direction. With distance-based protocols, each node forwards the packet to the neighbor closest to the destination. With progress-based protocols, each node forwards the packet to the neighbor that provides the most progress towards the final destination. Many measures of distances and progress have been proposed (e.g., [2], [7], [8], [13]). With direction-based (or compass) routing the packet is forwarded to the neighbor that minimizes the angle between the neighbor, the forwarding node itself, and the destination [10]. In general, greedy forwarding is efficient in dense networks where it is possible to make progress at each step (e.g., [14]).

B. Power-aware Routing

Wireless links in ad hoc and sensor networks are often highly unreliable. The existence of unreliable links exposes a key weakness in greedy forwarding protocols. While longer links may provide additional forward progress towards the final destination, such links are often less reliable and may require re-transmissions. Energy efficient routing protocols must therefore take the packet loss probabilities into consideration. To capture the energy and reliability tradeoffs pertaining to geographic forwarding, Zuniga *et al.* [9] proposed using a link-layer model of the Packet Reception Rate (PRR) [12]:

$$PRR(d) = (1 - \frac{1}{2}exp(-\frac{\gamma(d)}{2}\frac{1}{0.64}))^{\rho 8f}. \quad (1)$$

Here, d is the transmitter-receiver distance, γ the signal-to-noise ratio (SNR), ρ the encoding ratio, and f the frame length (assumed equal to 50 bytes). The SNR itself can be defined as $\gamma(d)_{dB} = P_t - PL(d) - P_n$, where P_t is the transmitted power, $PL(d)$ is the path loss, and P_n represents the noise floor. The model considers several environmental and radio parameters, such as the path-loss exponent (μ), the log-normal shadowing variance (σ), and the modulation and encoding schemes of the radio. Performance analysis of greedy forwarding strategies using the PRR metric can be found in [9].

Through passive monitoring and/or active probing, nodes can estimate the quality of the links to neighboring nodes. For example, effective algorithms to dynamically capture and store such information have been proposed and evaluated in the context of many-to-one data aggregation networks [15].

Haibo and Hong [16] present a power-aware geographic routing protocol that forwards the packets to the neighbor closest to what the authors refer to as the energy-optimal relay position. Other works have proposed power-aware techniques that attempt to balance the traffic among the nodes (proportional to their energy reserves, for example), in an attempt to extend the time until the first node failure occurs due to battery depletion [17], [18]. (This time is typically referred to as the lifetime of the network.)

C. Recovery Techniques

While greedy forwarding is efficient in dense networks, it may fail to find a path in the presence of dead areas, voids, or obstacles. In such networks, a packet may reach a point at which no progress towards the destination is possible (i.e., a “local minimum”). To avoid routing loops, techniques have been proposed that drop packets whenever a local minimum is reached, or a packet revisits a previously visited node [11].

Face routing (or perimeter routing) [3], [4], [19] is a scalable technique that can guarantee delivery in connected networks. With face routing, packets are forwarded around the faces of a planar graph, created by removing edges from the neighbor graph. Unfortunately, delivery guarantees are not always feasible in practice, and maintaining a planar graph structure may be costly. For example, mobility, heterogeneity, and imperfect communication devices may cause the neighbor graph to change frequently.

Limited flooding [2], [11] requires much less accurate state information about each node and its location. With these techniques a packet at a local minimum is flooded to all neighbors. The node performing the flooding then rejects any incoming copies of the packet. All receiving nodes forward the packet as usual, with the exception that they must retransmit the packet to the best neighbor that has not yet rejected the packet, until there is a neighbor that accepts the packet.

Many protocols have combined greedy routing with recovery mechanisms. For example, various greedy strategies have been combined with face routing [3], [4], [20]. Kim *et al.* [21] deployed a testbed and showed how these techniques can be made practical in real environments.

D. Random Walks

Random walks are a natural approach to graph exploration. In its simplest form, a packet is (at each step) forwarded to a node chosen randomly and uniformly from the current node’s neighbors. Rumor-based random walks [22] have been applied by long-lived search agents that record the path of each search query. Once an agent is informed of an event of interest, the recorded path can be used to route back to the originating node. Random walks have also been used to achieve load balancing in multi-path routing environments [23], [24].

This paper proposes a new power-aware geographic routing technique that uses biased random walks to bypass and recover from local minima. While a random-walk approach may require longer time for a packet to be delivered (than using limited flooding, for example) we have found that it typically requires fewer transmissions and hence lowers the energy consumption. We believe that this tradeoff is attractive in delay-tolerant environments in which minimizing energy consumption is important. We note that delivery guarantees could be handled using higher-level recovery mechanisms. To improve delivery times, our protocol could be extended to issue multiple parallel random walks. Based on recent findings by Alon *et al.* [25], such extensions could in some cases result in significant time reductions. This paper focuses on the energy efficiency and leaves such protocols for future work.

An alternative random-recovery approach is to route the packet towards a random intermediate target, at which point the packet's target is changed to the location of the actual destination [26]. This approach can be generalized by creating a path of anchor nodes along which packets can be routed [27]. This paper does not consider sender-defined approaches.

One of the main advantages with random walks is that if the location information of some set of nodes is incorrect or missing, it may still be possible to deliver the packet. We believe this property is especially attractive in mobile environments. In addition, random walk approaches inherently provide load balancing.

III. Protocol Design

This section introduces our routing algorithm. Similar to previous geographic routing algorithms, packets can be in one of two modes: *greedy* or *recovery*. In either mode, the protocol uses a distance metric that combines information about reception rates and relative forward progress. In greedy mode, the packets are always forwarded to the neighbor for which the metric has the largest value. In recovery mode, the packets are probabilistically forwarded based on the individual values of the metric for each of the neighboring nodes. Section III-A summarizes our routing algorithm, and Section III-B introduces the routing metrics used by the algorithm.

A. Routing Algorithm

Two power-aware distance metrics are used: G in greedy mode, and W in recovery mode. While we defer the exact details of these metrics to the next section, we note that both metrics combine information about the reception rates and the relative forward progress achieved when a node s forwards the packet towards a final destination node t via some neighbor $n \in N(s)$, where $N(s)$ is the set of neighbors of s. For simplicity, the algorithm requires that the greedy metric $G(s,n,t)$ is positive whenever node n is closer to the destination t than node s is to t, and non-positive otherwise. Similarly, we require that $W(s,n,t)$ is always non-negative.

By default, the algorithm begins in greedy mode. A minimum is reached whenever there is no neighbor $n \in N(s)$ that has a positive distance gain (or, given our constraint on G, whenever $G(s,n,t) \leq 0, \forall n \in N(s)$). If we let $d_{x,y}$ denote the distance between node x and y, this occurs whenever $d_{n,t} \geq d_{s,t}, \forall n \in N(s)$. See Figure 1. In this case, the distance $d_{s,t}$ is recorded (as the closest distance $d_{c,t}$ to the destination thus far) and the packet enters recovery mode, in which mode it remains until it reaches a new node s' that is closer to the destination than node s (i.e., until $d_{s',t} < d_{c,t}$). When such a node s' is reached the packet re-enters greedy mode.

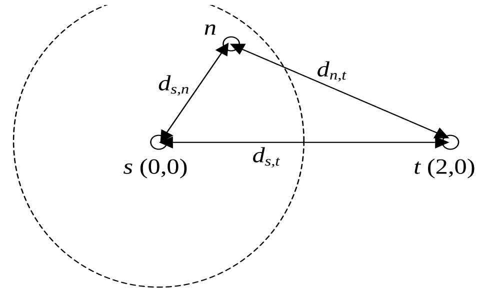


Fig. 1. Distances used by the progress metrics.

When in recovery mode, we use a biased random walk. In particular, each candidate node (i.e., neighbor $n \in N(s)$) is assigned a forwarding probability $Pr(n)$ proportional to $W(s,n,t)$; i.e., $Pr(n) = W(s,n,t)/\sum_{\forall n' \in N(s)} W(s,n',t)$.

Figure 2 summarizes our routing algorithm. As described above, we consider a packet to be routed from node s to a node t (Lines 1 and 2). At each routing step, until the packet reaches the final destination, the forwarding node s determines to which neighbor n to forward the packet. This node becomes the new sender s (Line 4.3).

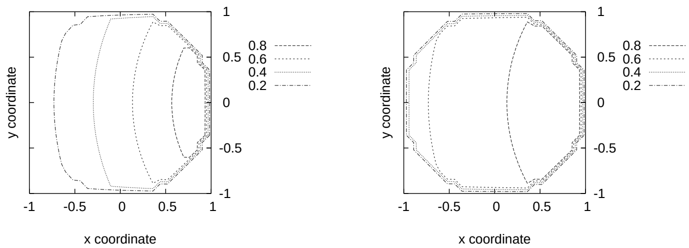
Let c be the node at which the packet was closest to the final destination (Lines 1 and 4.4). A packet is considered in greedy mode whenever it is not currently recovering from a minimum (i.e., $s = c$), and s has at least one neighbor n that provides progress towards the final destination (i.e., $\exists n \in N(s)$ s.t. $G(s,n,t) > 0$). In greedy mode, the packet is forwarded to the node n in this set with the highest $G(s,n,t)$ value (Line 4.1.1). Otherwise, the packet is in recovery mode, with each neighboring node n given a forwarding probability $Pr(n)$, proportional to $W(s,n,t)$ (Line 4.2.1).

1: $s, c \leftarrow$ [sending node]
2: $t \leftarrow$ [target node]
3: while $s \neq t$
4.1: if $c = s$ and $\exists n \in N(s)$ s.t. $G(s,n,t) > 0$; then
4.1.1: $n^* \leftarrow \text{argmax}_{\forall n \in N(s)} G(s,n,t)$
4.2: else
4.2.1: $n^* \leftarrow$ select using $Pr(n) \propto W(s,n,t)$
4.3: $s \leftarrow n^*$
4.4: if $d_{s,t} < d_{c,t}$; then
4.4.1: $c \leftarrow s$
5: end while

Fig. 2. The routing algorithm.

B. Routing Metrics

Both metrics G and W are defined as the product of (i) a power-aware routing metric based on the reception rates between individual node pairs, and (ii) a progress metric measuring the relative progress different candidates make towards the final destination. For the power-aware component we use the Packet Reception Rate (PRR), defined in equation (1).



(a) $f = 0$ (b) $f = 0.5$

Fig. 3. Weight of the second term in equation (4). Each contour line delimits a region with weights no less than the value associated with that line.

For simplicity, in greedy mode we use the relative Euclidian distance gain $(d_{s,t} - d_{n,t})/d_{s,t}$ as our progress metric:

$$G(s, n, t) = PRR(d_{s,n}) \cdot (1 - \frac{d_{n,t}}{d_{s,t}}). \qquad (2)$$

The combined power-aware greedy metric has been shown to perform well in dense networks [9] Of course, many alternative metrics are possible.

To ensure that each neighbor n has a non-negative weight $W(s, n, t)$, the recovery metric W uses weighted distance gains, rather than absolute distance gains. We scale gains such that the node furthest from t (at a distance $\max_{n' \in N(s)} d_{n',t}$) is given a weight 0, and the node closest to t (at a distance $\min_{n' \in N(s)} d_{n',t}$) is given a weight 1. Using linear scaling, the weighted distance gain $D(n)$ is given as follows:

$$D(n) = \frac{\max_{n' \in N(s)} d_{n',t} - d_{n,t}}{\max_{n' \in N(s)} d_{n',t} - \min_{n' \in N(s)} d_{n',t}}. \qquad (3)$$

To allow tuning of the bias towards nodes closer to the destination, the final metric uses a factor f weighted by the maximum value $D^* = \max_{n' \in N(s)} D(n')$:

$$W(s, n, t) = PRR(d_{s,n}) \cdot (fD^* + (1 - f)D(n)). \qquad (4)$$

Note that with $f = 0$ the full linear scale is used, and with $f = 1$ all nodes are given equal weight. Figure 3 shows the second term in equation (4) for the case when all neighbors are evenly spread within a disk of radius 1 from the sending node s, located at the origin, and the target node t is located at coordinate $(2, 0)$. Note that the power-aware component $PRR(d_{s,n})$ favors nodes closer to the sender.

IV. Performance Evaluation

This section presents preformance results for our new routing algorithm, and compares its performance to the performance of a number of benchmark algorithms.

A. Simulation Design and Methodology

Our simulations are based on existing Java code [28] modeling the Packet Reception Rate (PRR). We simulated the system for a large number of scenarios with different protocol parameters, network parameters, and/or number of nodes. For each scenario, ten different random node placements (topologies) were generated. For simplicity, each network occupies a rectangular region with a length:width raio of 4:5. Homogenous nodes, with equal transmission power, are scattered throughout this area using a uniform probability distribution. For each topology we simulated $10,000$ end-to-end packets (from a randomly selected sender s to a randomly selected target node t). We present the average values, as calculated over all ten topologies.

B. Candidate Algorithms

Four different routing algorithms are simulated:

- *Euclidian, without recovery*: Euclidian distance gains are used for greedy routing. No recovery mechanism.
- *Power-aware, without recovery* [9] Equation (2) is used for greedy routing, and packets are dropped when reaching a local minimum.
- *Power-aware, with biased recovery walk*: The proposed routing algorithm, as defined in Section III. Equation (2) is used for greedy routing and equation (4) is used for recovery routing.
- *Shortest path*: Global knowledge is used to find a path with the fewest hops between the source and the destination. Ties are broken randomly.

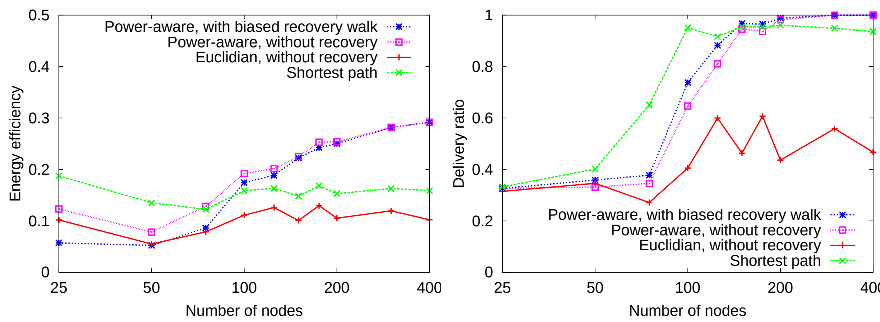
The above range of protocols allows us to compare how much performance improvement (if any) is due to power-aware greedy routing, and how much improvement is due to power-aware recovery. Future work will consider additional power-aware recovery mechanisms. The *Shortest path* algorithm is included as an abstract baseline policy. We note that it is an offline algorithm that typically is not feasible in practice.

C. Performance Comparison

Figures 4(a) and (b) show the average energy efficiency and delivery ratio, respectively, as functions of the number of nodes in the network. We define the energy efficiency as the number of packets successfully received per transmission. (This metric is proportional to the amount of data delivered per consumed unit of energy.) With 25 nodes the delivery ratio is small, as the network is not fully connected, and nodes typically can only forward packets to destinations close to them. With 200 nodes, on the other hand, the network is highly connected and both power-aware techniques are able to achieve a delivery ratio equal to 100%. These figures confirm that there is a significant advantage to power-aware routing in dense networks.

In this paper we focus on the region for which there is not always a greedy path, but the network is still connected. For this region, we note that the use of a recovery mechanism can significantly increase the delivery ratio (Figure 4(a)) at the expense of reduced energy efficiency (Figure 4(b)). Subsequent figures will focus on this tradeoff.

Of special interest is finding protocols that achieve a delivery ratio as high as possible, while ensuring that the routing algorithm is energy efficient. While both the energy efficiency and delivery ratio are outputs from our simulations, we illustrate the tradeoff between these quantities using a scatter plot. For each routing algorithm (and scenario), each data point represents a unique configuration of protocol parameters. Among the five curves shown in each graph in Figures 5 and 6,



(a) Average energy efficiency

(b) Average delivery ratio

Fig. 4. Policy comparison using our default scenario: size=40×50, $TTL = 50$, $f = 0.5$.

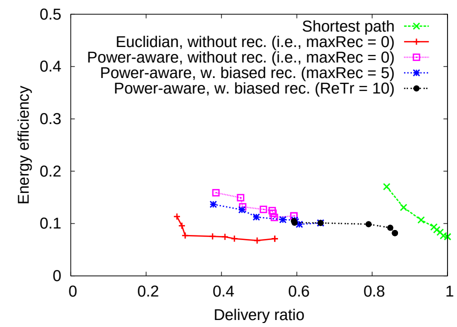
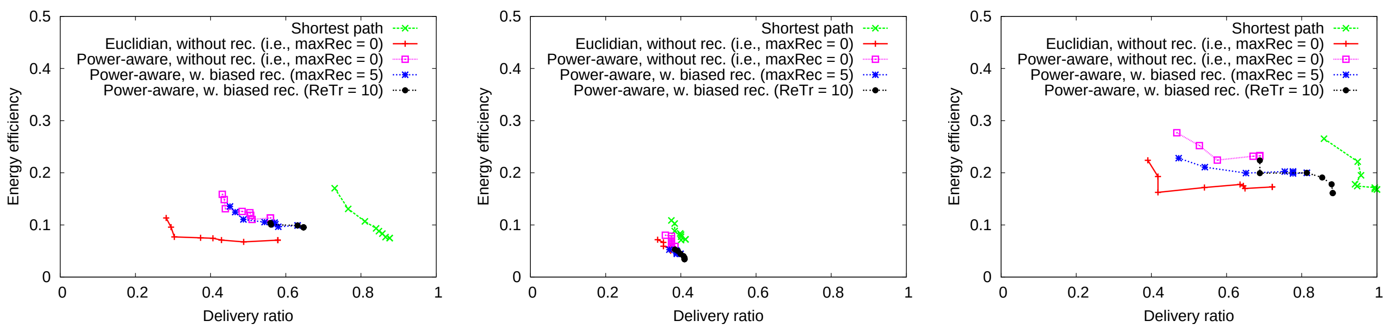
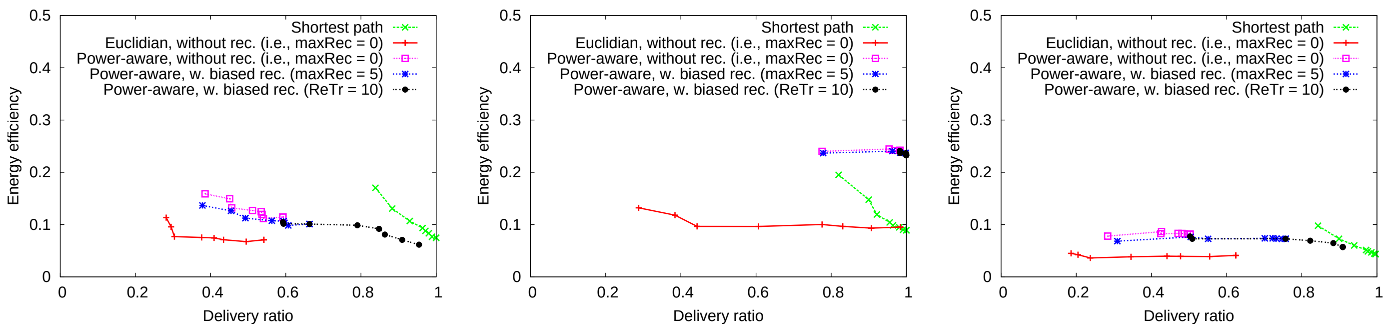


Fig. 5. Policy comparison using our default scenario: $n = 100$, size=40×50, $TTL = 50$, $f = 0.5$.



(a) $TTL = 10$ (b) $1/2\times$ density ($n = 50$) (c) $1/4\times$ area size ($20 \times 25; n = 25$)



(d) $TTL = 200$ (e) $2\times$ density ($n = 200$) (f) $4\times$ area size ($80 \times 100; n = 400$)

Fig. 6. Policy comparisons for a number example scenarios. The impact of TTL is illustrated by (a) and (d). The impact of the node density is illustrated by (b) and (e). The impact of the network size is illustrated by (c) and (f). (Default scenario: $n = 100$, size=40×50, $TTL = 50$, $f = 0.5$.)

four vary the maximum number of re-transmissions (using the following values 1, 4, 8, 12, 15, 20, 30, 50). For the proposed protocol we also show a curve in which the number of re-transmissions is fixed at 10, and the maximum number of consecutive hops in recovery mode is equal to: 1, 2, 5, 10, 20, (50, 100, 200).[2]

Results are shown for a number of example scenarios. The default scenario has $n = 100$ nodes, a network size of 40×50, $f = 0.5$, and a maximum time-to-live $TTL = 50$. These results are shown in Figure 5. Every other scenario differs in one characteristic. Figures 6(a) and (d) show results for smaller and larger time-to-live values, respectively. Figures 6(b) and (e) show results for networks with lower and higher node density, respectively. Figures 6(c) and (f) show results for smaller and larger networks, respectively.

[2]The maximum number of hops in recovery mode is further limited by the time-to-live (TTL) parameter used by each protocol, which limits the total number of transmissions per source-destination path.

Figure 5 shows that there is a significant advantage to using power-aware routing even for less dense networks. This is illustrated by the fact that points of the power-aware routing algorithms have higher values in both metrics. Second, and perhaps more importantly, we note that the probabilistic recovery mechanism substantially increases the delivery ratio with only a small decrease in energy efficiency. This is illustrated by the flat lines. For example, the highest delivery ratio without recovery (using 30 retransmissions) is 0.59; however, with no more than 10 retransmissions the new protocol can achieve a delivery ratio of 0.85. (This corresponds to an increase of 43%, while the energy efficiency is only reduced by 20%; from 0.114 to 0.092.)

Figure 6 shows that these observations are true for a wide range of scenarios. In fact, the recovery mechanism is particularly efficient in systems with larger TTL values

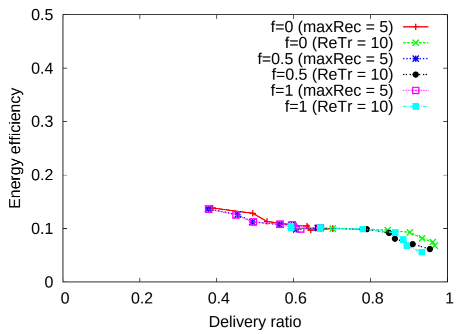


Fig. 7. Impact of f parameter: $n = 100$, size=40×50, $TTL = 200$.

(Figures 6(d)), for which the recovery algorithm has more time to locate recovery paths. The small range of potential delivery ratios in Figures 6(b) shows that there is very little that can be done when the density does not allow much connectivity. While it is rare that the recovery mechanism is used in dense networks (Figures 6(e)), we note its simplicity can also make it attractive in denser networks. For example, in the case that some nodes are damaged or out of power, the power-aware recovery mechanism allows the packet to recover without any additional information. Finally, while the energy efficiency is reduced by the (on average) longer paths in the larger networks, Figures 6(c) and (f) show that our general conclusions are independent of the network size.

Figure 7 shows that the results are relatively insensitive to the parameter choice f, though $f = 0$ achieves the highest delivery ratio. We expect aggressive random walks (smaller f) to be even more advantageous in mobile scenarios.

V. Conclusions

This paper proposes a new power-aware geographic routing protocol that combines power-aware greedy routing with power-aware random walks to bypass and recover from local minima. The proposed routing protocol is fully localized, energy efficient, and does not require any graph structure or routing-state information to be maintained. Our results show that the power-aware recovery mechanism can achieve significant improvements in delivery rates, compared to power-aware greedy protocols without a recovery mechanism, at the cost of only a small reduction in energy efficiency. Future work will consider alternative recovery mechanisms (using multiple parallel random walks, for example [25]) and evaluate the protocol under mobile scenarios (for which we expect biased random walks to be more efficient).

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