Position-Based Routing in Ad Hoc Networks

Ivan Stojmenovic, University of Ottawa and Universidad Nacional Autónoma de México

ABSTRACT

The recent availability of small, inexpensive low-power GPS receivers and techniques for finding relative coordinates based on signal strengths, and the need for the design of power-efficient and scalable networks provided justification for applying position-based routing methods in ad hoc networks. A number of such algorithms were developed recently. This tutorial will concentrate on schemes that are loop-free, localized, and follow a single-path strategy, which are desirable characteristics for scalable routing protocols. Routing protocols have two modes: greedy mode (when the forwarding node is able to advance the message toward the destination) and recovery mode (applied until return to greedy mode is possible). We shall discuss them separately. Methods also differ in metrics used (hop count, power, cost, congestion, etc.), and in past traffic memorization at nodes (memoryless or memorizing past traffic). Salient properties to be emphasized in this review are guaranteed delivery, scalability, and robustness.

INTRODUCTION

Ad hoc networks consist of wireless hosts that communicate with each other in the absence of a fixed infrastructure. They have potential applications in disaster relief, conference, and battlefield environments, and have received significant attention in recent years. Sensor networks are a class of wireless ad hoc networks. Wireless networks of sensors are likely to be widely deployed in the near future because they greatly extend our ability to monitor and control the physical environment from remote locations, and improve our accuracy of information obtained via collaboration among sensor nodes and online information processing at those nodes. Networking these sensors (empowering them with the ability to coordinate among themselves on a larger sensing task) will revolutionize information gathering and processing in many situations. Other contexts include rooftop networks, static networks with nodes placed on top of buildings, to be used when wired networks fail.

In an ad hoc network, a message sent by a node reaches all its neighboring nodes that are located at distances up to the transmission radius. Because of the limited transmission radius, the routes between nodes are normally created through several hops in such multihop wireless networks. In the widely accepted *unit* graph model, two nodes, A and B, in the network are neighbors if the distance between them is at most R, where R is the transmission radius that is equal for all nodes in the network. Variations of this model include unit graphs with obstacles (or subgraphs of unit graphs), and min-power graphs where each node has its own transmission radius and links are allowed only when bidirectional communication is possible. No credible research was done in literature on any other model other than the unit graph model (one important exception is in [1]). However, in power and cost savings and congestion-aware methods, nodes may adjust their transmission power to merely reach an intended receiver.

The use of the nodes' position for routing poses evident problems in terms of reliability. The accuracy of the destination's position is an important problem to consider. In some cases the destination is a fixed node (e.g., a monitoring center known to all nodes, or the geographic area monitored), and some networks are static. The problem of designing location update schemes to provide accurate destination information and enable efficient routing in mobile ad hoc networks appears to be more difficult than routing itself and will not be discussed here (a recent informative survey is given in [2]). We shall describe only the following simple strategy. If a message is reasonably "short," it can be broadcast (i.e., flooded) using an optimal broadcasting scheme (non-blind broadcasting schemes are discussed in [3]). If a message is relatively "long," destination search (or route discovery) can be initiated, which is a task of broadcasting a short search message. The destination then reports back to the source by routing a short message containing its position. The source is then able to route the full message toward the accurate position of the destination.

0163-6804/02/$17.00 © 2002 IEEE

Method	Loop-free	Localized	Path strategy	Metrics	Memory	Guar. del.	Scalability
Shortest path	Yes	No	Single-path	Hop count	No	Yes	No
Greedy [8], MFR [10]	Yes [11]	Yes	Single-path	Hop count	No	No	Yes
Compass (Kranakis+)	No [11]	Yes	Single-path	Hop count	No	No	Yes
LAR (Ko+), *DREAM*(Basagni+)	No [11]	Yes	Flooding	Hop count	Yes	No	No
Greedy/flooding [11]	Yes	Yes	Single/flooding	Hop count	Yes	Yes	Yes, dense
First response [14]	Yes	Yes	Single-path	Hop quality	No	No	Yes
Variable radius [13]	Yes	Yes	Single-path	Combined	No	No	Yes
GRA [5], *DFS*(Stojmenovic+)	Yes	Yes	Single-path	Hop count	Yes	Yes	Yes
Shortest power path (Ettus+)	Yes	No	Single-path	Power	No	Yes	No
Shortest cost path (Singh+)	Yes	No	Single-path	Cost	No	Yes	No
Shortest power-cost path	Yes	No	Single-path	Power-cost	No	Yes	No
Power aware [12]	Yes	Yes	Single-path	Power	No	No	Yes
power-face-power	Yes	Yes	Single-path	Power	No	Yes	Yes
Cost aware [12]	Yes	Yes	Single-path	Cost	No	No	Yes
cost-face-cost (Stojmenovic+)	Yes	Yes	Single-path	Cost	No	Yes	Yes
Power-cost aware [12]	Yes	Yes	Single-path	Power-cost	No	No	Yes
Face, *GFG* [15]	Yes	Yes	Single-path	Hop count	No	Yes	Yes
Robust GFG [1]	Yes	Yes	Single-path	Hop count	No	Yes	Yes

Table 1. *A taxonomy of position-based routing protocols.*

In this article we consider the routing task, in which a message is to be sent from a source node to a destination node in a given wireless network. The task of finding and maintaining routes in sensor and ad hoc networks is nontrivial since host mobility and changes in node activity cause frequent unpredictable topological changes. The destination node is known and addressed by means of its location. Routing is performed by a scheme based on this information, generally classified as a *position-based scheme*. Table 1 contains a quick synopsis/superset of the schemes discussed in this article.

ADVANTAGES OF USING POSITION IN ROUTING DECISIONS: LOCALIZED AD HOC ROUTES FOR SCALABILITY

The distance between neighboring nodes can be estimated on the basis of incoming signal strengths or time delays in direct communications. Relative coordinates of neighboring nodes can be obtained by exchanging such information between neighbors. Alternatively, the location of nodes may be available directly by communicating with a satellite (for outdoor networks), using GPS (Global Positioning System), if nodes are equipped with a small low power GPS receiver. The position-based approach in routing becomes practical due to the rapidly developing software and hardware solutions for determining absolute or relative positions of nodes in indoor/outdoor ad hoc networks [4].

The routing algorithms should perform well for wireless networks with an arbitrary number of nodes. Sensor and rooftop networks, for instance, have hundreds or thousands of nodes. While other characteristics of each algorithm are easily detected, *scalability* is sometimes judgmental and/or dependent on the performance evaluation outcome. A scalable solution is one that performs well in a large network. It has been experimentally confirmed [5, 6] that routing protocols that do not use geographic location in the routing decisions, such as *AODV*, *DSDV*, or *DSR* (a recent survey is given in [7]) are not scalable. For instance, [6] describes GLS (scalable location service), similar to the doubling circle method independently proposed by Amouris, Papavassiliou, and Lu in 1999. Experiments using the *ns* simulator for up to 600 mobile nodes show that the storage and bandwidth requirements of *GLS* grow slowly with the size of the network. Furthermore, *GLS* tolerates node failures well: query performance degrades gracefully as nodes fail and restart, and is relatively insensitive to node speeds [6]. Simple geographic forwarding [8] combined with *GLS* compares favorably with *DSR*; in large networks (over 200 nodes), it delivers more packets and consumes fewer network resources [6]. Similar conclusions were made in [5], where the depth-first search-based *GRA* scheme was compared with the *DSDV* protocol. Routing table sizes in *GRA* were logarithmic vs. linear for *DSDV* (e.g., ≈12 vs. ≈1000 in networks with 1024 nodes) [5]. Therefore, it is likely that only posi-

Robust strategies handle the position deviation due to the dynamicity of the network. Another aspect of robust algorithms is their ability to deliver a message when the communication model deviates from the unit graph, due to obstacles or noise.

tion-based approaches provide satisfactory performance for large networks. We shall now elaborate on other properties and reasons for difference in scalability.

Localized algorithms are distributed in nature and resemble greedy algorithms, where simple local behavior achieves a desired global objective. In a *localized* routing algorithm, each node makes a decision to which neighbor to forward the message based solely on the location of itself, its neighboring nodes, and the destination. In shortest- (weighted)-path-based nonlocalized algorithms, each node maintains accurate topology of the whole network. In addition, since nodes change between active and sleep periods, the activity status for each node is also required. Although routing-table- (typical nonposition)-based solutions merely keep the best neighbor information on a route toward the destination, the communication overhead for maintenance of routing tables due to node mobility and topology changes is quadratic in network size (each change in edge or node status may trigger routing table modifications in a large portion of the network). On the other hand, position-based localized algorithms avoid that overhead, by requiring only accurate neighborhood information and a rough idea of the position of the destination. For example, edge and node changes in one part of the network have no immediate impact on almost any route. Clearly, only localized algorithms provide scalable solutions, especially for networks with critical power-constrained resources at nodes (e.g., sensor networks).

PATH STRATEGIES, METRICS, MEMORIZATION, GUARANTEED DELIVERY, LOCATION UPDATES, AND ROBUSTNESS

Desirable qualitative properties of routing protocols include distributed operation, loop freedom (to avoid a worst case scenario of a small fraction of packets spinning around in the network), demand-based operation, and "sleep" period operation (when some nodes become temporarily inactive).

The shortest path route is an example of a *single-path* strategy, where one copy of the message is in the network at any time. Arguably, the ideal localized algorithm should follow a single path. On the other extreme are *flooding*-based approaches, where messages are flooded through the whole network area or portion of the area. The "compromise" is a *multipath* strategy, a route composed of few single recognizable paths. Since power and bandwidth are two main limitations in wireless networks, single-path strategies are preferred.

The metrics used in simulations normally reflect the goal of the designed algorithm, and are naturally decisive in route selection. Most routing schemes use *hop count* as the metric, where hop count is the number of transmissions on a route from a source to a destination. However, if nodes can adjust their transmission power (knowing the location of their neighbors), the constant per hop metric can be replaced by a *power* metric that depends on distance between nodes. The goal is to minimize the energy required per each routing task. Some nodes participate in routing packets for many source-destination pairs, and the increased energy consumption may result in their failure. Thus, the pure power consumption metric may be misguided in the long term, and longer paths that pass through nodes that have plenty of energy may be a better solution. The *cost* metric (a rapidly increasing function of decreasing remaining energy at a node) is used with the goal of maximizing the number of routing tasks a network can perform. Current congestion and other metrics can also be used.

Solutions that require nodes to memorize routes or past traffic are sensitive to node queue size, changes in node activity, and node mobility while routing is ongoing (e.g., monitoring environment). It is better to avoid memorizing past traffic at any node if possible. However, the need to memorize past traffic is not necessarily a demand for significant new resources in the network for several reasons. First, a lot of memory space is available on tiny chips. Next, the memorization of past traffic is needed for short periods of time while an ongoing routing task is in progress, and therefore after a timeout outdated traffic can be safely removed from memory. Finally, the creation of a quality of service (QoS) path (i.e., a path with bandwidth, delay, and connection time requirements) requires that the path is memorized in order to optimize the traffic flow and satisfy QoS criteria.

The delivery rate is the ratio of numbers of messages received by the destination and sent by senders. The primary goal of every routing scheme is to deliver the message, and the best assurance one can offer is to design a routing scheme that will *guarantee delivery*. Wireless networks normally use a single-frequency communication model where a message intended for a neighbor is heard by all other neighbors within the transmission radius of the sender. Collisions normally occur in medium access schemes, such as IEEE 802.11. This article focuses on guaranteed delivery in routing (i.e., eventual delivery), which is conditional on the ability of the medium access layer to always transmit a message between any two neighboring nodes, possibly with retransmissions.

Robust strategies handle the position deviation due to the dynamicity of the network. Another aspect of robust algorithms is their ability to deliver a message when the communication model deviates from the unit graph, due to obstacles or noise. Robust variants of algorithms described here are given in [1, 9].

We shall first present routing schemes for *greedy mode*, when the node currently holding the message may advance it toward the destination. The "advance" may be defined in different ways (e.g., distance to destination), or may not be measured at all, leading sometimes to nonloop-free schemes. The basic distance, progress, direction, power, cost, power-cost, congestion, and fading channel methods belong to this group. Greedy mode routing was shown to nearly guarantee delivery for dense graphs, but to fail frequently for sparse graphs. Next, we shall review the schemes applied for the *recovery mode*. The routing process is converted from the greedy mode to recovery mode at a node where greedy mode fails to advance a message toward the destination (referred to as the *concave node* in the sequel). We shall review the following schemes for dealing with the recovery mode: greedy/flooding, depth-first search-based routing, anchored geodesic packet forwarding, and greedy-face-greedy routing. They all allow return from recovery mode to greedy mode, and aim at guaranteed delivery.

GREEDY ROUTING SCHEMES

In a localized routing scheme, node S, currently holding the message, is aware only about the position of its neighbors within the transmission radius and destination D (indicated by black circles in Fig. 1).

Takagi and Kleinrock [10] proposed the first position-based routing scheme, based on the notion of progress. Given a transmitting node S, the progress of a node A is defined as the projection onto the line connecting S and D. In the *Most Forward within Radius* (MFR) scheme [10], the packet is forwarded to a neighbor whose progress is maximal (e.g., node M in Fig. 1). Nelson and Kleinrock also discussed a random progress method (choosing at random one of the nodes with progress, and adjusting the transmission radius to reach that node), arguing that there is a trade-off between progress and transmission success. Hou and Li discussed the *Nearest Forward Progress* (NFP) method (selecting node N in Fig. 1).

Finn [8] proposed the greedy routing scheme based on geographic distance. S selects neighboring node G (Fig. 1) that is closest to the destination among its neighbors. Only neighbors closer to the destination than S are considered. Otherwise, there is a lack of advance, and the method fails. A variant of this method is called the Geographic Distance Routing (GEDIR) scheme [11]. In this variant, applied on other schemes as well, all neighbors are considered, and the message is dropped if the best choice for a current node is to return the message to the node the message came from (stoppage criterion indicating lack of advance). The *Nearest Closer* (NC) method was proposed in [12] (node N in Fig. 1).

In the *compass routing* method (also referred to as the DIR method) proposed by Kranakis, Singh, and Urrutia (e.g., [11]), message m is forwarded to neighbor A (Fig. 1), such that direction SA is closest to direction SD (i.e., the angle $\angle ASD$ is minimized).

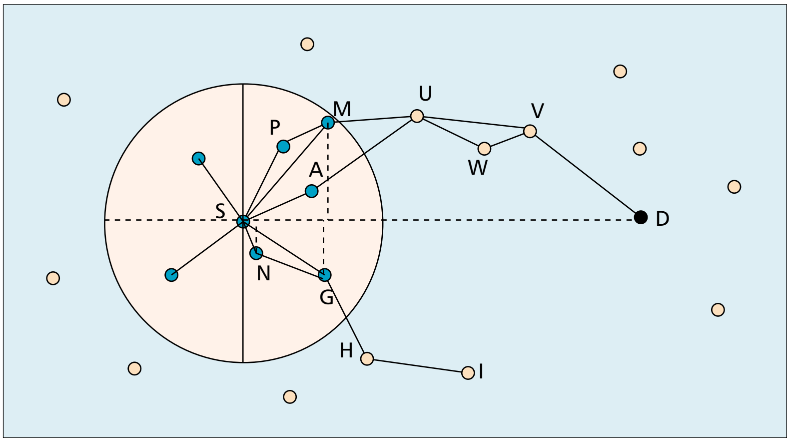

Figure 1. S *selects* M *in* MFR *path* SMUVD, G *in greedy path* SGHI *that fails to deliver,* A *in direction-based-path* SAUWVD, P *in power path* SPMUWVD, N *in* NFP/NC *path* SNGHI *that fails to deliver.*

The MFR and greedy/GEDIR methods, in most cases, provide the same path to the destination and are loop-free [11]. The hop count for the DIR method is somewhat higher than for the greedy scheme, while the success rate is similar. All methods have high delivery rates for dense graphs, and low delivery rates for sparse graphs (about half the messages at average degrees below 4 are not delivered) [11]. When successful, hop counts of greedy and MFR methods nearly match the performance of the shortest path algorithm. The DIR method, and any other method that includes forwarding the message to a neighbor with closest direction (e.g., DREAM and LAR), are not loop-free (see [11] for counterexample and references).

Hop count was traditionally used to measure the energy requirement of a routing task, thus using a constant metric per hop. However, if nodes can adjust their transmission power, the constant metric can be replaced by a power metric $u(d) = d^{\alpha} + c$ (for some constants α and c) that depends on distance d between nodes. The value of c, which includes energy lost due to start up, collisions, retransmissions, and acknowledgments, is relatively significant, and protocols using any kind of periodic hello messages are extremely energy inefficient.

A localized *power-aware routing algorithm* is described in [12]. It is based on a formula and an intuition. For two given nodes, [12] described a formula on the optimal power needed for transmission between the two nodes, assuming that additional nodes can be placed at will, whose desirable position is described. Of course, such nodes are not available in a given ad hoc network, but nevertheless the result is used to attempt to find the most promising forwarding neighbor. It should be as close to the destination as possible, but also as close as possible to the optimal position of a forwarding node for the power optimal transmission. The current node S will forward the packet to a neighbor B for which the sum of power for transmitting from S to B and ideal (optimal) power from B to D is minimized. The algorithm proceeds until the destination is reached, or no closer node to the destination exists.

Singh, Woo, and Raghavendra proposed a cost metric as a function proportional to the inverse of the remaining battery power. Power and cost are combined into a single metric in order to choose power-efficient paths among cost-optimal ones. Localized cost and power-cost efficient algorithms were proposed in [12], and their performance, when successful, was surprisingly competitive with shortest weighted path algorithms.

Other metrics for choosing the best forwarding neighbor in localized routing schemes were considered recently. Yeh [13] proposes several variable-radius routing protocols for achieving

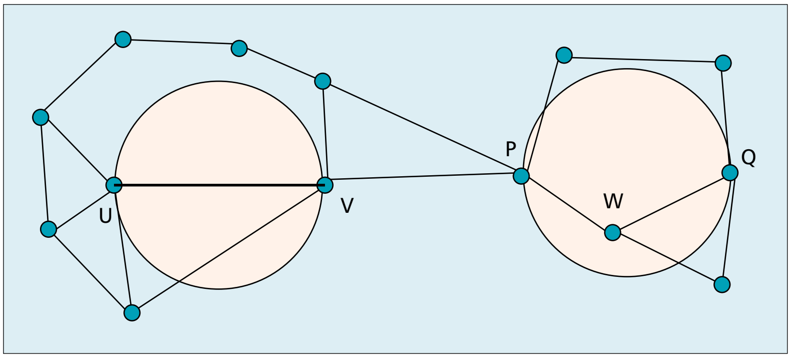

Figure 2. *Gabriel graph contains edge* UV *but not edge* PQ *since node W is inside the disk.*

higher throughout, smaller latency at a given traffic load, and/or lower power consumption in ad hoc networks. Larsson [14] described a forwarding method for routing in multihop networks that takes into account Raleigh fading and nonfading channels. Candidate nodes, addressed in the data packet header, who successfully receive the data packet return acknowledgments in consecutive order (e.g., as their addresses are listed in the packet header). The first neighbor to respond is the forwarding neighbor.

GUARANTEED DELIVERY WITH MEMORIZATION

We shall now discuss techniques proposed to route from concave nodes (normally defined as nodes that have no closer neighbor to destination than themselves) that switch from greedy to recovery mode. A simple *greedy/flooding* method is proposed in [11]: concave nodes flood their neighbors, and then reject further copies of the same message. Each neighbor then continues with greedy routing, except nodes that announce their concavity are ignored in forwarding decisions. For each message seen by a node, a list of concave neighbors to be avoided is memorized. If a node is left without a "willing" neighbor, it does not forward the packet further. The method was subsequently improved so that one neighbor in each connected component of the neighborhood subgraph receives a forwarding message from the concave node.

Terminode routing [9] addresses scalability, robustness, collaboration, and simplicity of nodes. This routing scheme is a combination of two protocols called Terminode Local Routing (TLR) and Terminode Remote Routing (TRR). TLR is a mechanism that allows reaching destinations in the vicinity of a terminode and does not use location information for making packet-forwarding decisions. TRR is used to send data to remote destinations and uses geographic information. The major novelty is the Anchored Geodesic Packet Forwarding (AGPF) component of TRR. This is a source-path-based method designed to be robust for mobile networks. Instead of using traditional source paths (i.e., lists of nodes), it uses anchored paths. An anchored path is a list of fixed geographical points called *anchors*. The packet loosely follows the anchored path. At any point, the packet is sent in the direction of the next anchor in the anchored path by applying a greedy routing scheme. When a terminode finds that the next anchor geographically falls within its transmission range, it deletes it from the anchored path and sends in the direction of the new next anchor. This is repeated until the packet is sent in the direction of the final destination.

Geographic routing algorithm (GRA) by Jain, Puri, and Sengupta [5] requires nodes to partially store routes toward certain destinations (those for which they are concave) in routing tables. GRA applies the greedy strategy in forwarding messages. However, concave nodes start the route discovery protocol, if the information in routing tables in outdated. The route discovery finds a path from S to D and updates the routing tables toward D at any node on the path with this information. After the route discovery protocol is successfully completed, the stuck packet can be routed from S to D. The authors propose two route discovery strategies: *breadth first search* (equivalent to flooding) and *depth first search* (DFS). DFS yields a single acyclic path from S to D. Each node puts its name and address on the route discovery packet p. Then it forwards p to a neighbor who has not seen p before. This neighbor is one of all the neighbors that minimize $d(S, y)+d(y, D)$, where $d(x, y)$ is the distance between nodes x and y. If a node has no possibilities to forward the packet, it removes its name and address from the packet and returns the packet to the node from which it originally received it. Route discovery packets are kept for some time. If a node receives the same packet twice, it refuses it. DFS can alternatively be used to deliver the packet without route discovery and routing tables, as independently proposed by the author of this tutorial (with applications for the construction of QoS paths).

STATELESS ROUTING WITH GUARANTEED DELIVERY

Stateless routing schemes are localized schemes where nodes do not need to memorize past traffic. All decisions are based on the location of neighboring nodes, location of the destination, the position of the neighboring node that forwarded the message in the previous step, and the information that arrives with the message. The *face* and Greedy-Face-Greedy (GFG) routing schemes were described by Bose, Morin, Stojmenovic, and Urrutia [15], with subsequent improvements, such as the use of two-hop neighborhood information and the dominating set concept [3]. Most important, Barriere, Fraigniaud, Narayanan, and Opatrny [1] made GFG robust against interferences by addressing instability in the transmission ranges of the host.

In order to ensure message delivery, the face algorithm [15] constructs a planar and connected so-called Gabriel subgraph (GG) of the unit graph, and then applies routing along the faces of the subgraph that intersect the imaginary line between the source and the destination.

GG is a spanning subgraph of the original network. It is defined as follows: given any two

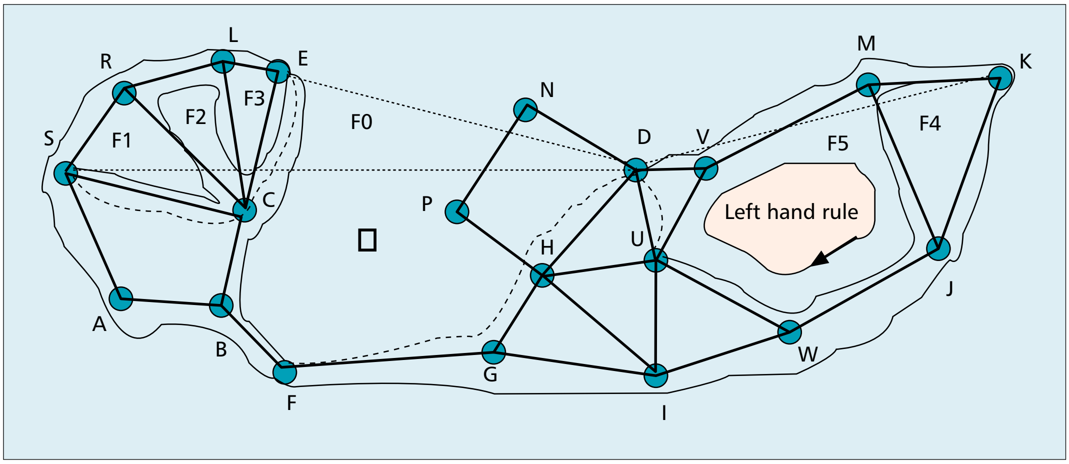

Figure 3. *Routes from* S *to* D*: face route* SCRLCELRSABFGIWJKMVD *traversing faces F1, F2, F3, and F0 and GFG route* SCE-ECBF-FGHD*; routes from* K *to* D: face *route* KMJWU-UD *traversing faces F4 and F5 and GFG = greedy route* KMVD.

adjacent nodes U and V in the network, the edge UV belongs to GG if and only if no other node W of the network is located in the disk with UV as its diameter. This test is fully localized, and requires no additional information other than the position of all neighboring nodes. Figure 2 illustrates the test, and gives examples of edge UV that belongs to GG and edge PQ that does not (it also shows the whole GG). Gabriel graph is planar, that is, no two edges of it intersect each other. The intersection of GG and the unit graph is connected since both of them contain a minimal spanning tree as a subgraph [15].

Once the GG is extracted from the network, routing is performed along its edges. Its planarity and its connectivity ensure message delivery by routing along the faces of the graph. An illustration of face routing is given in Fig. 3, which only shows edges of GG, not the full unit graph.

If a face is traversed using the left hand rule, a loop will be created, since the face will never be exited (see face F5 in Fig. 3). Forwarding in the left hand rule is performed using the directional approach. Node J receiving message from neighbor M will find neighbor W that minimizes angle MJW, measured counterclockwise ($\angle MJM = 2\pi$). The escape from a face and entering into a neighboring face occurs at advancing intersections of the imaginary line SD from source S to destination D with traversed edges. Face change normally means rule change, but sometimes it does not (the selected face is the one on the same side of the edge as D). For example, in Fig. 3 the right hand rule is applied on F1, F3, and F4, while left hand rule is applied on F2, F0, and F5. The face route can also be extremely long, such as route *SCRLCELRSABFGIWJKMVD* from S to D in Fig. 3, indicated as the scribbled line, which follows the outer face of the graph. However, face routing is only applied in the recovery mode of the GFG routing algorithm [15]. As soon as a node has a neighbor closer to the destination than the concave node that switched to the recovery mode, the algorithm goes back to the greedy mode. For instance, the route from S to D starts in greedy mode *SCE*, then switches to recovery mode at E and follows face route *ECBF* until node F is reached that has a neighbor closer to D than concave node E. Greedy route *FGHD* then reaches the destination. Figure 3 also illustrates alternate routes from node K to D. The face route *KMJWU* may end at node U that is a neighbor of D (otherwise path *UVMVD* will be added), while greedy route *KMVD* succeeds without ever calling the recovery mode.

CONCLUSION

A taxonomy of described position-based routing schemes is given in Table 1. It also describes the main characteristics of each scheme. The performance of these schemes also depends on network density. Greedy schemes have performance close to performance of an optimal shortest path (weighted) algorithm for dense graphs, but low delivery rates for sparse graphs. Schemes that guarantee delivery may have high communication overhead for sparse graphs.

This review did not include discussion of relevant issues such as physical requirements, experimental design, location updates, QoS, congestion, scheduling node activity, topology construction, broadcasting, and network capacity.

The successful design of localized single-path loop-free algorithms with guaranteed delivery is an encouraging start for future research. The search for localized routing methods that have excellent delivery rates, short hop counts, small flooding ratios, and power efficiency is far from over. In QoS applications, memorization does not appear to require additional resources and is therefore acceptable. However, the research on QoS position-based routing is scarce.

Further research is needed to identify the best GPS-based routing protocols for various network contexts. These contexts include nodes positioned in three-dimensional space and obstacles, nodes with unequal transmission powers, or networks with unidirectional links. Finally, the mobility-caused loop needs to be further investigated, and solutions found and incorporated in position-based routing schemes.

Greedy schemes have a performance close to performance of optimal shortest path (weighted) algorithm for dense graphs, but have low delivery rates for sparse graphs. Schemes that guarantee delivery may have high communication overhead for sparse graphs.

In QoS applications, memorization does not appear to require additional resources and is therefore acceptable. However, the research on QoS position based routing is scarce.

REFERENCES

[1] L. Barriere *et al.*, "Robust Position Based Routing in Wireless Ad Hoc Networks with Unstable Transmission Ranges," *Proc. 5th ACM Int'l. Wksp. Discrete Algorithms Methods for Mobile Comp. and Commun.*, 2001, pp. 19–27.

[2] I. Stojmenovic, "Location Updates for Efficient Routing in Ad Hoc Networks," *Handbook of Wireless Networks and Mobile Computing*, Wiley, 2002, http://www.site.uottawa.ca/~ivan, pp. 451–71

[3] I. Stojmenovic, M. Seddigh, and J. Zunic, "Dominating Sets and Neighbor Elimination Based Broadcasting Algorithms in Wireless Networks," *IEEE Trans. Parallel Dist. Sys.*, vol. 13, no. 1, Jan. 2002, pp. 14–25.

[4] J. Hightower and G. Borriello, "Location Systems for Ubiquitous Computing," *IEEE Comp.*, Aug. 2001, pp. 57–66.

[5] R. Jain, A. Puri, and R. Sengupta, "Geographical Routing Using Partial Information for Wireless Ad Hoc Networks," *IEEE Pers. Commun.*, Feb. 2001, pp. 48–57.

[6] J. Li et al., "A Scalable Location Service for Geographic Ad Hoc Routing," *Proc. ACM MOBICOM 2000*, pp. 120–30.

[7] Y.C. Tseng, W.H. Liao, and S.L. Wu, "Mobile Ad Hoc Networks and Routing Protocols," *Handbook of Wireless Networks and Mobile Computing*, I. Stojmenovic, Ed., Wiley, 2002, pp. 371–92.

[8] G. G. Finn, "Routing and Addressing Problems in Large Metropolitan-Scale Internetworks," ISI res. rep. ISU/RR-87-180, Mar. 1987.

[9] L. Blazevic *et al.*, "Self-organization in Mobile Ad Hoc Networks: The Approach of Terminodes," *IEEE Commun. Mag.*, June 2001, pp. 166–75.

[10] H. Takagi and L. Kleinrock, "Optimal Transmission Ranges for Randomly Distributed Packet Radio Terminals," *IEEE Trans. Commun.*, vol. 32, no. 3, 1984, pp. 246–57.

[11] I. Stojmenovic and Xu Lin, "Loop-free Hybrid Single-Path/Flooding Routing Algorithms with Guaranteed Delivery for Wireless Networks," *IEEE Trans. Parallel Dist. Sys.*, vol. 12, no. 10, 2001, pp. 1023–32.

[12] I. Stojmenovic and Xu Lin, "Power-Aware Localized Routing in Wireless Networks," *IEEE Trans. Parallel Dist. Sys.*, vol. 12, no. 11, 2001, pp. 1122–33.

[13] C. Yeh, "Variable-Radius Routing Protocols for High Throughput, Low Power, and Small Latency in Ad Hoc Wireless Networks," *IEEE Int'l. Conf. WLANs and Home Nets.*, Dec. 2001.

[14] P. Larsson, "Selection Diversity Forwarding in a Multihop Packet Radio Network with Fading Channel and Capture," *Proc. ACM MobiHoc 2001*, pp. 279–82.

[15] P. Bose *et al.*, "Routing with Guaranteed Delivery in Ad Hoc Wireless Networks," *3rd Int'l. Wksp. Discrete Algorithms Methods Mobile Comp. Commun.*, Seattle, WA, Aug. 20, 1999, pp. 48–55; also in *ACM/Kluwer WL Nets.*, vol. 7, no. 6, Nov. 2001, pp. 609–16.

BIOGRAPHY

IVAN STOJMENOVIC (ivan@site.uottawa.ca) received his Ph.D. degree in mathematics in 1985. His research interests include wireless, interconnection, and neural networks, parallel computing, and multiple-valued logic. He has published more than 150 different papers in journals and conferences, and edited *Handbook of Wireless Networks and Mobile Computing* (Wiley, 2002). He has held regular or visiting positions in Yugoslavia, Japan, the United States, Canada, France, and Mexico.