POSITION BASED ROUTING ALGORITHMS FOR AD HOC NETWORKS: A TAXONOMY

Silvia Giordano Silvia.Giordano@epfh.ch
ICA-DSC-EPFL CH-1015 Lausanne (Switzerland),

Ivan Stojmenovic ivan@site.uottawa.ca
SITE, University of Ottawa, Ottawa, Ontario K1N 6N5, Canada and
DISCA, IIMAS, UNAM, Direccion Circuito Escolar s/n, Ciudad Universitaria, Coyoacan, Mexico D.F., Mexico

Ljubica Blazevic Ljubica.Blazevic@epfh.ch
ICA-DSC-EPFL CH-1015 Lausanne (Switzerland),

Abstract

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 in last few years, in addition to few basic methods proposed about fifteen years ago. This article surveys known routing methods, and provides their taxonomy in terms of a number of characteristics: loop-free behavior, distributed operation (localized, global or zonal), path strategy (single path, multi-path or flooding based), metrics used (hop count, power or cost), memorization (memoryless or memorizing past traffic), guaranteed delivery, scalability, and robustness (strategies to handle the position deviation due to the dynamicity of the network). We also briefly discuss relevant issues such as physical requirements, experimental design, location updates, QoS, congestion, scheduling node activity, topology construction, broadcasting and network capacity.

1. Introduction

Mobile ad hoc networks (often referred to as MANETs) consist of wireless hosts that communicate with each other in the absence of a fixed infrastructure. They are used in disaster relief, conference and battlefield environments, and received significant attention in recent years [IETF, MC]. A class of wireless ad hoc networks that is currently subject of intensive research is sensor network. 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 amongst themselves on a larger sensing task) will revolutionize information gathering and processing in many situations. Sensor networks have been recently studied in [EGHK, HCB, KKP]. Rooftop networks, proposed in [Sh], are not mobile, but are deployed very densely in metropolitan areas (the name refers to an antenna on each building's roof, for line-of-sight with neighbors) as an alternative to wired networking. Such a network also provides an alternative infrastructure in the event of failure of the conventional one, as after a disaster. A routing system that self-configures (without a trusted authority to configure a routing hierarchy) for hundreds of thousands of such nodes in a metropolitan area represents a significant scaling challenge. Commercial examples of static ad hoc networks include Metricom Ricochet [M] and Nokia Rooftop [N] systems. Other similar contexts where the material surveyed in this article is applicable are wireless local area networks, packet radio networks, home and office networks, spontaneous networks [FAW, G] etc.

A widely accepted basic graph-theoretical model for all mentioned networks is the *unit* graph model, defined in the following way. Two nodes *A* and *B* in the network are neighbors (and thus joined by an edge) if the Euclidean distance between their coordinates in the network is at most *R*, where *R* is the transmission radius which is equal for all nodes in the network. Variation of this model include unit graphs with obstacles (or subgraph of unit graph), minpower graphs where each node has its own transmission radius and links are unidirectional or allowed only when bi-directional communication is possible. However, no credible research was done in literature on any other model other than unit graph model (one important exception in [BFNO]). Figure 1 gives an example of a unit graph with transmission radius as indicated. Because of limited transmission radius, the routes are normally created through several hops in such multi-hop wireless network. For most algorithms reviewed here, the unit graph model is used in experiments, while the algorithm itself may be applied for arbitrary graph.

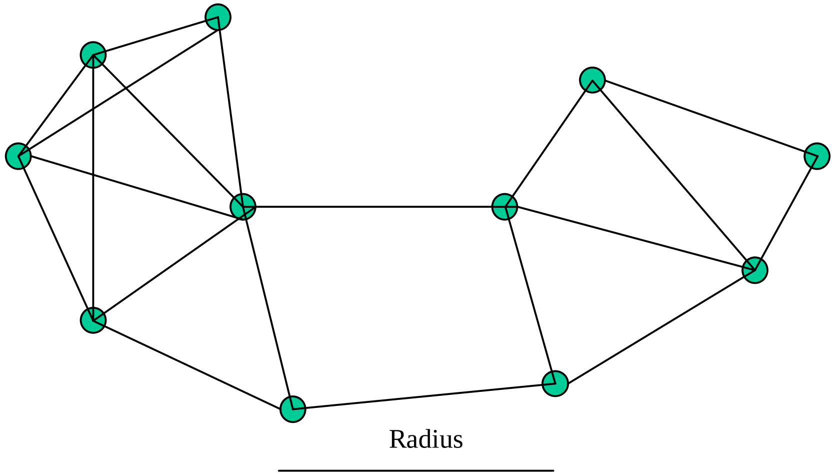

Figure 1. Unit graph representation of multi-hop wireless network

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 mobile networks is nontrivial since host mobility and changes in node activity status cause frequent unpredictable topological changes. The destination node is known and addressed by means of its location. Routing is performed by a scheme that is based on this information, that is generally classified as *position-based scheme*.

The distance between neighboring nodes can be estimated on the basis of incoming signal strengths. Relative coordinates of neighboring nodes can be obtained by exchanging such information between neighbors [CHH]. Alternatively, the location of nodes may be available directly by communicating with a satellite, using GPS (Global Positioning System), if nodes are equipped with a small low power GPS receiver. The surveys of protocols that do not use geographic location in the routing decisions are given in [BMJHJ, RS, RT]. This survey will discuss only position-based approaches.

2. *Position-based Routing Protocols Taxonomy*

Macker and Corson [MC] listed qualitative and quantitative independent metrics for judging the performance of mobile ad hoc networks routing protocols. Desirable qualitative properties 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). We shall further elaborate on these properties and metrics. Our goal is to provide a taxonomy of existing position based routing algorithms in light of qualitative characteristics listed below.

a) Loop-freedom. The proposed routing protocols should be inherently loop-free, to avoid timeout or memorizing past traffic as cumbersome exit strategies. Proposed algorithms are therefore classified as having or not having loop free property.

b) Distributed operation. Localized algorithms [EGHK] are distributed algorithms that resemble greedy algorithms, where simple local behavior achieves a desired global objective. In a *localized* routing algorithm, each node makes decision to which neighbor to forward the message based solely on the location of itself, its neighboring nodes, and destination. Non-localized algorithms can be classified as global or zonal ones. In a *global* routing algorithm, each node is assumed to know the position of every other node in the network. In addition, since nodes change between active and sleep periods, the activity status for each node is also required. When such global knowledge is available, the routing task becomes equivalent to the shortest path problem, if hop count is used as main performance metrics (such an algorithm is described in [BCS, SWR]). If power or cost metrics are used instead, the shortest weighted path algorithm may be applied, as described in [RM] for power and in [SWR] for cost metric. Between the two extremes is the *zonal* approach, where network is divided into zones, with localized algorithm applied within each zone, and shortest path or other scheme applied for routing between zones [JL, LAR]. Clearly, localized algorithms are preferred if they can nearly match the performance of non-localized ones. An expanded locality is sometimes considered. For example, if two hop neighbors are included, the algorithm is classified as *2-localized*.

c) Path strategy. 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 message is flooded through the whole network area (broadcasting solves routing, and in high mobility scenario this could be optimal solution [HOTV], if optimized [PL, QVL, SSZ]), or portion of the area [BCSW, KV]. The ‘compromise’ is *multi-path* strategy, that is route composed of few single recognizable paths. Some algorithms are combinations of two strategies, and are appropriately labeled (e.g. single-path/flooding, single-path/multi-path).

d) Metrics. The metrics that is used in simulations normally reflects the goal of designed algorithm, and is naturally decisive in the route selection. Most routing schemes use *hop count* as the metrics, where hop count is the number of transmissions on a route from a source to destination. This choice of metric agrees with the assumption that nodes cannot adjust (that is, reduce) their transmission radii in order to reach desired neighbor with minimal power. It also assumes that delay is proportional to hop count (when the impact of congestion is not significant), and that the (both energy and bandwidth) cost of starting communication with neighbor is considerable (this is supported by the analysis in [Fe, FN]). However, if nodes can adjust their transmission power (knowing the location of their neighbors) then the constant metric can be replaced by a *power* metric that depends on distance between nodes [E, RM, HCB]. The goal is to minimize the energy required per each routing task. However, some nodes participate in routing packets for many source-destination pairs, and the increased energy consumption may result in their failure. Thus pure power consumption metric may be misguided in the long term, and longer path that passes through nodes that have plenty of energy may be a better solution. The *cost* metric (a rapidly increasing function of decreasing remaining energy at node) is used with the goal of maximizing the number of routing tasks that network can perform.

e) Memorization. Solutions that require nodes to memorize route 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 period of time, while ongoing routing task is in progress, and therefore after a timeout outdated traffic can be safely removed from memory. Finally, the creation of Quality-of-Service (QoS) path, that is, path with bandwidth, delay, and connection time [SRV] requirements, requires that the path is memorized in order to optimize the traffic flow and satisfy QoS criteria. This certainly includes the use of the best path found in the search process. Once destination is reached, the optimal path can be reported back to source.

f) Guaranteed message delivery. Delivery rate [BMJHJ] is the ratio of numbers of messages received by destination and sent by senders. The primary goal of every routing scheme is to delivery the message, and the best assurance one can offer is to design routing scheme that will guarantee delivery. Wireless networks normally use single frequency communication model where a message intended for a neighbor is heard by all other neighbors within transmission radius of sender. Collisions are normally occurring in medium access schemes mostly used, such as IEEE 802.11. The guaranteed delivery property assumes the application of an ideal, collision free, medium access scheme, such as time division multiple access, or acknowledgement/retransmission scheme that is assumed to be always successful otherwise.

g) Scalability. The routing algorithms should perform well for wireless networks with arbitrary number of nodes. Sensor and rooftop networks, for instance, have hundreds or thousands of nodes. Scalable single-path strategies, such as shortest-path, have $O(\sqrt{n})$ overhead, where n is the number of nodes in the network. While other characteristics of each algorithms are easily detected, scalability is sometimes judgmental, and/or dependent on performance evaluation outcome. We shall apply a simplified (although arguable) criterion, that a routing scheme is scalable if it is loop-free, localized, and single-path. Note that, several schemes, are proved to guarantee the messages delivery (and to be loop free) in the static case. It is not clear how these schemes handle loops and perform delivery in the case of node mobility. We name these loops due to the position of some nodes as *mobility-caused loops*. These loops are in general temporary loops that appear because some nodes move in a position that causes the packet to loop. This situation cannot be easily detected because it arises after the direction for packet has been chosen.

In this work we classify as loop free and delivery guarantee, as traditionally done, all schemes that are proved to be loop free and which guarantee the message delivery, even if they are not proved for the mobility-caused loops.

h) Robustness The use of nodes' position for routing poses evident problems in terms of reliability. The accuracy of destination position is an important problem to consider. In some cases the destination is a fixed node (such as monitoring center known to all nodes, or the geographic area that is monitored), some networks are static which makes the problem straightforward, while the problem of designing location updates schemes to enable efficient routing in mobile ad hoc network appears to be more difficult than routing itself (see a recent survey [S4]) and will not be discussed here unless it is integral part of presented method.

For small networks, in the absence of any useful information about destination location (that is, a clever location update scheme), the following simple strategy can be applied. If message is reasonably 'short', it can be broadcasted (that is, flooded), using an optimal broadcasting scheme [PL, QVL, SSZ]. If message is relatively 'long' then destination search (or route discovery [BJMHJ]) can be initiated, which is a task of broadcasting short search message. Destination then reports back to source by routing a short message containing its position. The source then is able to route full message toward accurate position of destination.

However, in large networks, the algorithms that assume that the position of destination is 'reasonably' accurate are not able to deal with eventual position deviation, and impose high mobility tracking overhead. More robust and scalable routing algorithms must, by design, be able to cope with the network dynamicity or can have backup strategies that allow to reach a node even when the node deviated from the known position.

Another aspect of robust algorithms is their ability to deliver message when communication model deviates from unit graph, due to obstacles or noise. One such model is investigated in [BFNO].

Performance of most algorithms surveyed in this paper will be discussed in terms of delivery rates and hop counts obtained in simulations, for graphs of various densities (measured by average degrees, that is, average number of neighbors of each node). This suffices for single-path strategies, but is misleading for flooding based or multi-path ones. Due to limited battery power, the communication overhead must be minimized if number of routing tasks is to be maximized. Purely proactive methods that maintain routing tables with up-to date routing information or global network information at each node are certainly unsatisfactory solution, especially when node mobility is high with respect to data traffic. For instance, shortest path based solutions are too sensitive to small changes in local topology and activity status (the later even does not involve node movement). Since localized algorithm should compete with the best (shortest path) algorithm (instead of competing with the worst, flooding, algorithm, as compared in [KV]), the *flooding rate* was introduced in [SL2] as a measure of communication overhead. Flooding rate is the ratio of the number of message transmissions and the shortest possible hop count between two nodes. Each transmission in multiple routes is counted, and a message can be sent to all neighbors with one transmission. Note that the cost of location updates is not counted in the flooding rate, although it should be added to the total communication overhead.

We can distinguish five main classes of existing position based routing schemes:

- Basic Distance, Progress, and Direction Based Methods
- Partial Flooding and Multi-Path Based Path Strategies
- Depth First Search Based Routing with Guaranteed Delivery
- Nearly Stateless Routing with Guaranteed Delivery
- Power and Cost Aware Routing

The remaining of this paper is organized as follows: first we analyze the characteristic of each class and then describe and compare the schemes that present aspect of this class. Clearly, some schemes fall in more than one class and are, thus, discussed in more than one section. Finally, we summarize the described position based routing schemes behaviour with respect to the given taxonomy.

3. Basic Distance, Progress, and Direction Based Methods

The notion of progress is the key concept of several GPS based methods proposed in 1984-86 . Given a transmitting node *S*, the *progress* of a node *A* is defined as the projection onto the line connecting *S* and the final destination.of the distance between *S* and the receiving node A neighbor is in *forward direction* if the progress is positive (for example, for transmitting node *S* and receiving nodes *A*, *C* and *F* in Fig. 1); otherwise it is said to be in *backward direction* (e.g. nodes *B* and *E* in Fig. 1). Basic Distance, Progress, And Direction Based Methods use these concepts to select among neighbors the next routing step.

Schemes as the *Random Progress* Method [NK], *Most Forward within Radius* [TK], *Nearest Forward Progress* [HL], the *Greedy Scheme* [F], the *Nearest Closer* [SL] and all its variants (the *2-Hop Greedy Method* [SL2] the *Alternate Greedy* method [LS], the *Disjoint Greedy* method [LS], and *GEDIR* [SL2]), and the *Compass Routing* method [KSU], fall in this class.

In the ***random progress method*** [NK], packets destined toward *D* are routed with equal probability towards one intermediate neighboring node that has positive progress. The rationale for the method is that, if all nodes are sending packets frequently, probability of collision grows with the distance between nodes (assuming that the transmission power is adjusted to the minimal possible), and thus there is a trade-off between the progress and transmission success.

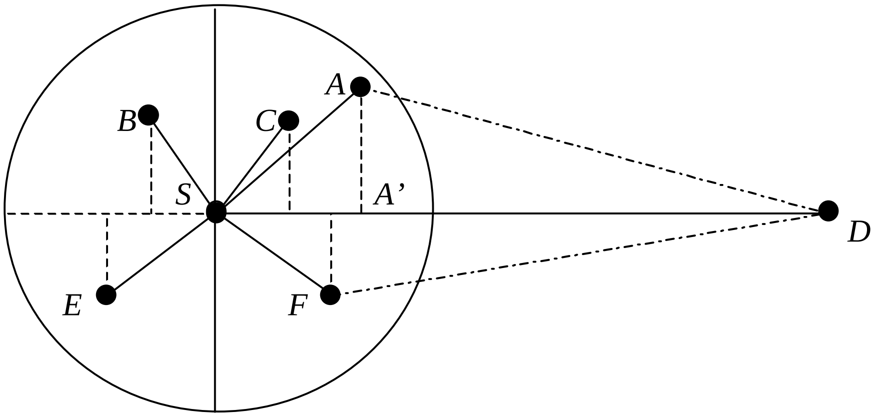

Figure 1. Positive and negative progress: *C, A, F* are in forward direction, with a positive progress (for example, *A’D* < *SD*); nodes *B* and *E* are in backward direction, with a negative progress.

Takagi and Kleinrock [TK] proposed ***MFR* (most forward within radius)** routing algorithm, in which packet is sent to the neighbor with the greatest progress (e.g. node *A* in Fig. 1). *MFR* is probed to be a loop-free algorithm [SL2]. *MFR* is the only progress-based algorithm competitive in terms of hop count.

In [HL], the method is modified by proposing to adjust the transmission power to the distance between the two nodes. In this scheme, packet is sent to the nearest neighboring node with forward progress (for instance, to node *C* in Fig. 1).

In 1987, Finn [F] proposed, the **greedy scheme** as *variant of random progress method*, which 'allows choosing as successor node any node, which makes progress toward the packet's destination'. The optimal choice would be possible only with the complete topological knowledge of the network.. To bypass this problem, Finn adopted the *greedy* principle: select the node closest to the destination. In the example of Fig. 2, the sender *S* selects node *B* which is closer to *D* than the other neighbor *A*. The path selected by the algorithm is *SBEFGHID* and consists of seven hops. When none of neighboring nodes is closer to the destination than current node *C*, Finn [F] proposes to search all *n*-hop neighbors (nodes at distance at most *n* hops from current node, where *n* is network dependent parameter) by flooding the nodes until a node closer to destination than *C* is found. The algorithm has non-trivial details and does not guaranty delivery, nor optimize flooding rate. The author argued that his algorithm has no loops, since it always forces message to make a step closer to the destination.

A variant of greedy algorithms, called ***GEDIR***, is proposed in [SL2]. In this variant, the message is dropped if the best choice for a current node is to return the message to the node the message came from. It increases delivery rate by prolonging failure. The same criterion can be applied to MFR method, and directional methods described below.

Greedy routing was applied as part of other routing schemes. For instance, in [APL, LJCKM], each node applies greedy routing scheme, but uses the last reported location of destination, which may be outdated, but, as the message progresses toward destination, closer nodes increase accuracy of destination information. Location updates schemes used in [APL] is based on doubling size of circles of location updates. This idea has been rediscovered one year later in [LJCKM].

GEDIR is often used as basic ingredient in other routines. For instance, it is used in several location update schemes, such as quorum based [S1] and home agent based schemes [BBCGHL, MJKLD, S3, WS] (note that the later scheme was independently proposed in four papers).

In ***2-hop greedy method*** [SL2] node *A* selects the best candidate node *C* among its 1-hop and 2-hop neighbors according to the corresponding criterion. Then A forwards *m* to its best 1-hop neighbor in the set of neighbors of *A* and *C*. This basic idea is applicable also to most other methods listed in the sequel (the table presenting taxonomy includes only this one).

In the ***alternate greedy*** method [LS], the *i*-th received copy of *m* is forwarded to *i*-th best neighbor, according to the selected criterion (it fails if number of copies exceeds number of neighbors). In the ***disjoint greedy*** method [LS], each intermediate node, upon receiving *m,* will forward it to its best neighbor among those who never received the message (it fails if no such neighbor exists). These methods reduce failure rate compared to greedy method, by memorizing past traffic.

In the ***compass routing*** method (referred here to as the ***DIR*** method) proposed by Kranakis, Singh and Urrutia [KSU], the source or intermediate node *A* uses the location information of the destination *D* to calculate its direction. Then the message *m* is forwarded to the neighbor *C*, such that the direction *AC* closest to the direction *AD*. This process repeats until the destination is, eventually, reached. Consider the network on Fig. 2, where the radius is equal to edge *EF.* The direction *AC* is closest to direction *AD* among candidate directions *AS, AB, AC,* and *AP*. The path selected by *DIR* method is *SACJKLMND*.

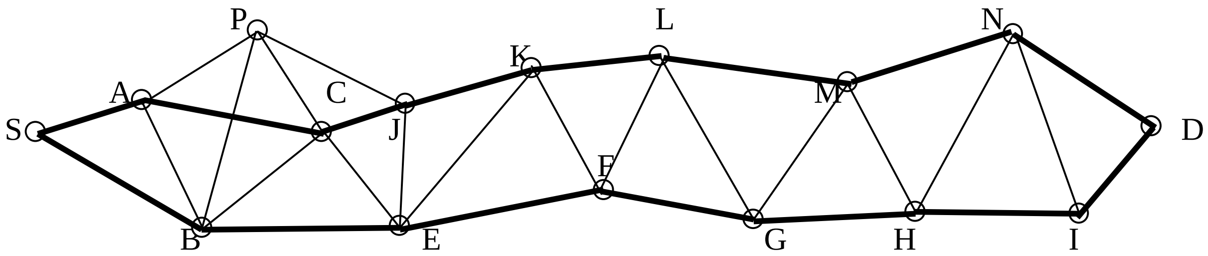

Figure 2. Paths selected by *DIR (SACJKLMND)* and *GEDIR (SBEFGHID)* algorithms

The *MFR* and *greedy* methods, in most cases, provide the same path to destination. Simulation in [SL2] revealed that nodes in *greedy* and *MFR* methods select the same forwarding neighbor in over 99% of cases, and, in the majority of the cases, the whole paths were identical (e.g. Fig. 2).. The hop count for *DIR* method is somewhat higher than for GEDIR, while success rate is similar. All methods have high delivery rates for dense graphs, and low delivery rates for sparse graph (about half messages at average degrees below 4 are not delivered). 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 message to neighbor with closest direction, such as *DREAM* [BCSW], are not loop-free, as shown in [SL2] using the counterexample shown in Figure 3. The loop consists of four nodes, denoted *E, F, G* and *H.* The graph is an unit graph and the radius as indicated in the figure. Let the source be any node in the loop, e.g. *E.* Node *E* selects node *F* to forward the message, because the direction of *F* is closer to destination *D* than the direction of its other neighbor *H.* Similarly node *F* selects *G,* node *G* selects *H* and node *H* selects *E.* Additional nodes *C* can be taken outside the loop nodes, so that message can be delivered from *E* to *D* by alternate path.

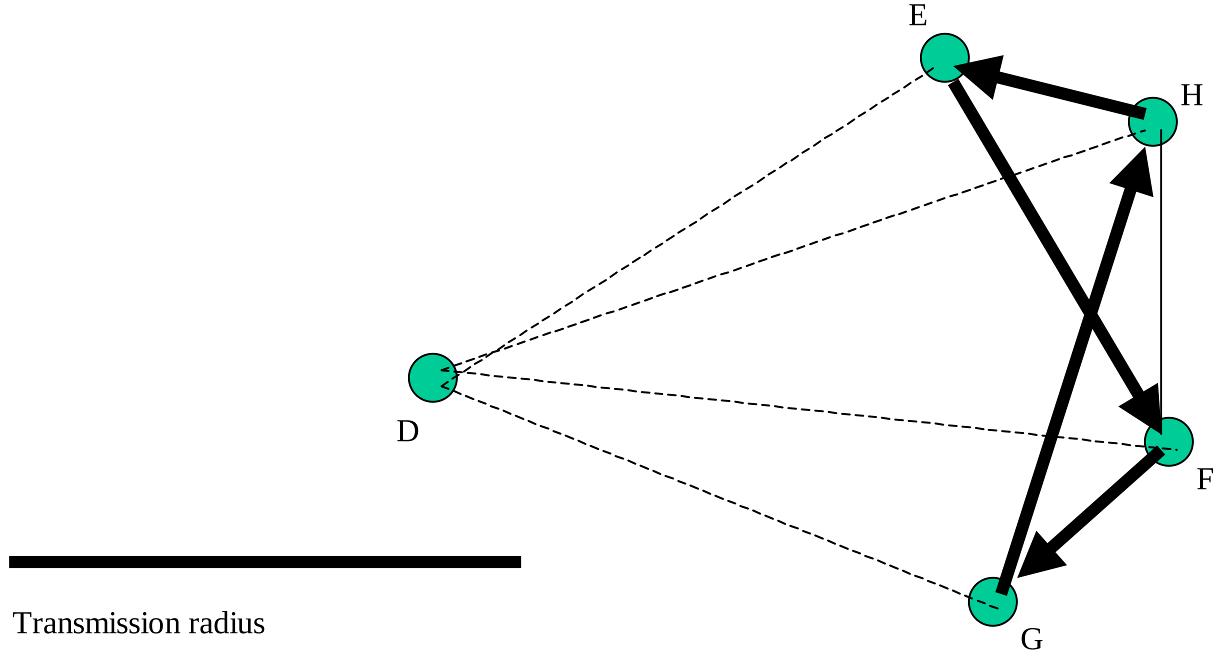

Figure 3. A loop in the directional routing

3. Partial Flooding and Multi-Path Based Path Strategies

In directional flooding-based routing methods, a node *A* transmits a message *m* to several neighbors whose direction (looking from *A*) is closest to the direction of destination *D.* In order to control flooding effect, flooding based method require nodes to memorize past traffic, to avoid forwarding the same message more than once.

DREAM [BCSW], *LAR* {KV], *V-GEDIR* [S2], *CH-MFR* [S2] belong to this class. Flooding can be partial because it is directed towards nodes in a limited sector of the network (e.g. in *DREAM* or in *LAR*) or because it is stopped after a certain number of hops (e.g. in *flooding GEDIR* family of schemes). Moreover, partial flooding can be used only for path discovery purpose (e.g. *LAR*) or for packet forwarding (e.g. *DREAM*).

In ***DREAM*** protocol [BCSW], *m* is forwarded to all neighbors whose direction belongs to the selected range, determined by the tangents from *A* to the circle centered at *D* and with radius equal to a maximal possible movement of *D* since the last location update. *DREAM* algorithm [BCSW] is a proactive protocol that uses a limited flooding of location update messages.

In the ***location aided routing (LAR)*** algorithm [KV], the request zone (the area containing the circle and two tangents)is fixed from the source, and nodes, which are not in the request zone, do not forward a route request to their neighbors. In *LAR scheme 2 [KV]*, the source or an intermediate node *A* will forward the message to all nodes that are closer to the destination than *A*. The control part of *LAR* protocol is, essentially, equivalent to *DSR* flooding protocol [BMJHJ], restricted to the request zone. Therefore all nodes inside an area receive the routing packet, and the algorithm is therefore of partial flooding nature, causing excessive flooding rates [CL, SL2].

[S2] discusses ***V-GEDIR*** and ***CH-MFR*** methods in order to reduce flooding rate and provide loop-free behavior for a scheme that forwards *m* to several neighbors at each step. , The message *m* is forwarded to exactly those neighbors, which may be the best choices for the possible position of destination (using the distance or progress criterion, respectively). In *V-GEDIR* method, these neighbors are determined by intersecting the Voronoi diagram of neighbors with the circle (or rectangle) representing the possible positions of destination. The portion of the convex hull of neighboring nodes is analogously used in the *CH-MFR* method.

In order to avoid message dropping, [SL2] proposes a modification to *greedy/GEDIR* and *MFR* algorithms as follows: When the basic algorithm would drop the message at a 'concave' node *A*, in the modified version *A* floods it to all its neighbors. Then withdraws from the network for further copies of the same message *m* (that is, its neighbors do not forward *m* to *A* in future decisions). Since *A* is connected to *D*, at least one of its neighbors is also connected to *D*, therefore the algorithm guarantees the delivery of the message. The methods will be refereed to as ***flooding greedy/GEDIR*** *(GEDIR* variant in this case is better option, since flooding is postponed (that is: reduced) or avoided in some cases), and *flooding MFR* (abbreviated as *f-greedy, f-GEDIR, f-DIR* and *f-MFR*) [SL2]. In addition to guaranteed delivery and loop-free behavior, experiments in [SL2] report also reduced flooding rates compared to *LAR* [KV] and *DREAM* [BCSW] schemes. For dense graphs it approaches greedy method performance, providing delivery in rare failure events. For sparse graphs it does causes partial flooding. The method has been improved in [LLS]: In this solution, the message is forwarded to only one neighbor of each connected components of the sub-graph consisting of neighbors of concave node *A*. Since there are at most four connected components of neighbors of any concave node in unit graph model, the number of newly created components is at most three (note that one existing component terminates at concave node). However, while a new component is sometimes created, the creation of two or three components is a rare event in practice. The partial flooding impact of *f-GEDIR* is reduced to multi-path impact in this scheme, called the ***component routing***. The creation of multiple 'parallel' paths is justified by the inability of a localized algorithm to decide which of global routes leads toward destination.

In the ***multi-path*** method [LLS], the source node *S* forwards *m* to *c* best neighbors according to distance from *D*. Each of *c* created copies afterwards follows the greedy, alternate, or disjoint method (these copies may interact since copy numbers are not communicated). Therefore one can consider *c-greedy, c-alternate* or *c-disjoint* methods [LLS]. The experiments indicate significant gain in delivery rate for $c=2$, some gain for $c=3$ and no significant gains for $c>3$. The flooding rate increases with *c*, and it seems that only value $c=2$ justifies the use of additional resources.

A different approach using flooding and multipath routing is the one taken in ***Terminode routing*** [BGL]. Terminode routing addresses by design the following objectives: scalability (both in terms of the number of nodes and geographical coverage); robustness; collaboration and simplicity of the 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 to 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; it is the key element for achieving scalability and reduced dependence on intermediate systems. 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, that is lists of nodes, it uses anchored paths. An anchored path is a list of fixed geographical points, called anchor. The packet loosely follows anchored path. At any point, the packet is sent in the direction of the next anchor in the anchored path by applying geodesic packet forwarding. 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 direction of the final destination. Figure4 illustrates the operation of *AGPF.*

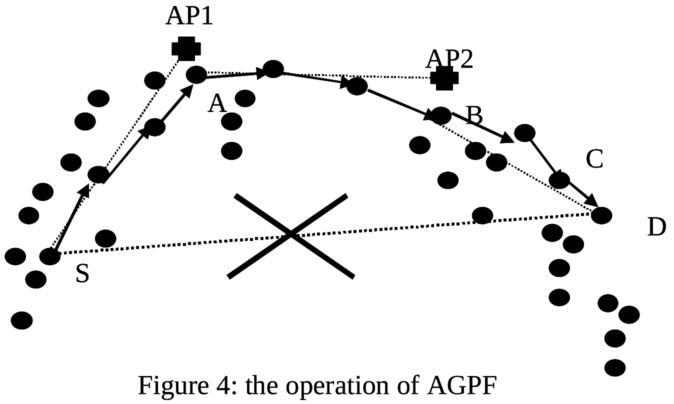

Figure 4: the operation of AGPF

The figure presents how *AGPF* works when the source *S* with *EUI*$_S$ has some data to send to a terminode *D* with *EUI*$_D$ and there is no connectivity along the shortest line from *S* to *D. S* has an anchored path to *D* given by a list of geographical locations called anchored points: *{AP1, AP2}.* First, geodesic packet forwarding in the direction of *AP1* is used. After some hops the packet arrives at a terminode *A* which finds that it is close to *AP1.* At *A* the packet is forwarded by using geodesic packet forwarding in the direction of *AP2.* Second, when the packet comes to *B* that is close to *AP2,* it starts sending the packet towards *D*. Last, when the packet comes to *C* it finds that *D* is *TLR*-reachable and forwards the packet to *D* by means of *TLR.*

GPF is both used between anchors in *AGPF* and as default method to send data to remote destinations when *AGPF* does not apply. Additionally, *TRR* has a component, Anchored Path Discovery (*APD*), which offers two methods to obtain anchored paths. The simulation results for mobile ad-hoc networks composed of several hundreds of terminode demonstrate benefits of the combination of *TLR* and *TRR* over an existing protocol that uses geographical information for packet forwarding [BGL].

4. *Depth First Search Based Routing with Guaranteed Delivery*

Single-path strategies that guarantee delivery of the message to the destination are very relevant for supporting loss sensitive traffic. *Geographic Routing Algorithm* [JPS] and the *Depth First Search* Based Algorithm proposed in [SRV] schemes are based on this concept.

Jain, Puri and Sengupta [JPS] proposed one such strategy called ***geographic routing algorithm (GRA)***, and it requires nodes to partially store routes toward certain destinations in routing tables. *GRA* applies greedy strategy in forwarding messages. However, sometimes node *S* may discover that it is closer to the destination *D* than any of its neighbors. That is, the packet may be ‘stuck’ at *S*. Under this condition, it starts the route discovery protocol. 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 that 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* (which is 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 which minimize $d(S,y)+d(y,D)$, where $d(x,y)$ is Euclidean 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 twice the same packet, it refuses it. The authors investigate routing table sizes and present methods for taking into account positional errors, node failures and mobility.

Another *depth first search* based algorithm has been independently proposed in [SRV]. The algorithm does not use routing tables, and instead message follows the whole depth first search path from *S* to *D*. Next, each node *S* minimizes $d(S,D)$, and therefore the algorithm is equivalent to greedy method whenever it exists a node closer to *D* than *S*. For dense graphs most of the paths generated by this method are the same as the paths obtained by the greedy method. The authors discuss also the application of this method for the creation of quality-of-service (QoS) paths, that is, paths that satisfy delay and bandwidth criteria. In particular, they propose to use, as criterion, the connection time, which is time node *S* predicts to have link with any of its neighbor based on speed and direction of movements of *S* and its neighbor. In a simplified model considered in [SRV], delay can be decomposed into propagation delay proportional to the hop count, and demand for additional bandwidth. In this model, edges with no sufficient bandwidth are simply ignored in the process. Additionally, the delay criterion reduces the search to finding a path with hop count no longer than a given maximum. When this maximum is reached, the greedy forwarding stops and the route discovery message is returned back in order to search another branch that might have shorter path. The nodes which remain on the created path memorize the forwarding and previous node on the path. When the so created path reaches the destination *D*, *D* can report it back to *S* along the path itself, and *S* can start sending to *D*. The algorithm can be evaluated in terms of length of route discovery path and length of created route.

5. *Nearly Stateless Routing with Guaranteed Delivery*

Nearly Stateless Routing with Guaranteed Delivery are schemes where nodes maintain only some local information to perform routing. The ***Face Routing*** and ***GFG*** **(Greedy-Face-Greedy)** schemes were described by Bose, Morin, Stojmenovic and Urrutia [BMSU], subsequently improved in [DSW] by applying dominating set concept and adding a shortcut 2-hop procedure.

Recently, Barriere, Fraigniaud, Narayanan and Opatrny [BFNO] made them robust against intereferences. Karp and Kung [KK] transformed *GFG* algorithm into ***GPSR (Greedy Perimeter Stateless Routing)*** protocol by including IEEE 802.11 medium access control scheme. They experimented with mobile nodes moving according to a random waypoint model, using ns-2 environment, and compared it with non-position based *DSR* protocol [BMJHJ], assuming accurate destination information. *GPSR* protocol consistently delivered over 94% (mobility may introduce disconnection) data packets successfully; it is competitive with *DSR* in this respect on 50 node networks, and increasingly more successful than *DSR* as the number of nodes increases. The routing protocol traffic generated by GPSR was constant as mobility increased, while *DSR* must query longer routes with longer diameter and do so more often as mobility increases (with less effective caching). Thus *DSR* generates drastically more routing protocol traffic in simulations with over 100 nodes [KK]. Therefore the scalability seems to be the major advantage of this class of algorithms over source based protocols.

In order to ensure message delivery, the *face* algorithm [BMSU] (called *perimeter* algorithm in [KK]) constructs planar and connected so-called Gabriel subgraph of the unit graph, and then applies routing along the faces of the subgraph (e.g. by using the right hand rule) that intersect the line between the source and the destination.

If a face is traversed using the right hand rule then a loop will be created, since face will never be existed (see an illustration in Figure F). Forwarding in right hand rule is performed using directional approach. To improve the efficiency of the algorithm in terms of routing performance, face routing can be combined with greedy routing [F] to yield *GFG* algorithm. Routing is mainly greedy, but if a mobile host fails to find a neighbor closer than itself to the destination, it switches the message from ‘greedy’ state to ‘face’ state.

Nearly stateless schemes are likely to fail if there is some instability in the transmission ranges of the mobile host. Instability in the transmission range means that the area a mobile host can reach is not necessarily a disk and the range can vary between $r=(1-\varepsilon)R$ and R, $\varepsilon>0$. Barriere, Fraigniaud, Narayanan and Opatrny [BFNO] considered such kind of instability, and proposed this model as a generalization of unit graph. With this model they are able to handle the unstable situations where nodes may or may not communicate directly. This situation occurs if there are obstacles (e.g. buildings, bad weather) that disrupt the radio transmission.

6. *Power and Cost Aware Routing*

Hop count was traditionally used to measure energy requirement of a routing task, thus using constant metric per hop. However, if nodes can adjust their transmission power (knowing the location of their neighbors) then the constant metric can be replaced by a power metric that depends on distance between nodes [E, RM, HCB]. While the computational power of the devices used in the network is rapidly increasing, the lifetime of batteries is not expected to improve much in the future. We see a clear need for improvement in power consumption in existing routing algorithms. Schemes that combine position based and power/cost aware routing are proposed in [RM], [Fe], [FN], [LHBWW], [LH], [LWWF], [E], [HCB], [SRW], [CT], [GCNB], [SL2], [SL], [LAR], [SD].

Rodoplu and Meng [RM] proposed a general model where the power consumption between two nodes with distance d is given by $u(d)=d^{\alpha}+c$ for some constants α and c, and describe several properties of power transmission that are used to find neighbors for which direct transmission is the best choice in terms of power consumption. Alternatively, $u(d)=ad^{\alpha}+c$ can be applied, to obtain measurements in desired units.

The investigation [Fe, FN] of energy consumption of existing IEEE 802.11 based ad hoc network interfaces shows that the constant c cannot be ignored (although most articles in literature assume $c=0$). In other words, energy required to start up communication, which includes energy lost due to collisions, retransmissions and acknowledgements, is relatively significant. Protocols using any kind of periodic hello messages, frequently used in ad hoc network literature, are extremely energy inefficient, since energy and bandwidth metric cannot be equated [Fe, FN].

Rodoplu and Meng [RM] also described a shortest weighted path based algorithm for finding power optimal routes from any source to a given fixed destination. They first construct power optimal enclosure graph rooted at each destination.

The graph structure was reduced in [LHBWW, LH]. A sparse power efficient topology for wireless networks, based on Gabriel and Yao structures, is described in [LWWF]. However, [LHBWW, LH, LWWF] assume $c=0$, and their constructions and proofs are not applicable for the case $c>0$. Therefore they do not improve of results presented in [RM] if the realistic model with $c>0$ is considered.

A localized *power aware routing algorithm* is described in [SL]. It is based on the following theorem proved in [SL]. Let d be the distance between the source and the destination. The power needed for direct transmission is $u(d)=ad^{\alpha} + c$ which is optimal if $d \leq (c/(a(1-2^{1-\alpha})))^{1/\alpha}$. Otherwise $n-1$ equally spaced nodes can be selected for retransmissions, where $n= d(a(\alpha-1)/c)^{1/\alpha}$ (rounded to nearest integer), producing minimal power consumption of about $v(d)= dc(a(\alpha-1)/c)^{1/\alpha} + da(a(\alpha-1)/c)^{(1-\alpha)/\alpha}$. 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. The forwarding neighbor should be as close to destination as possible, but also as close as possible to the optimal position of forwarding node in the theorem. Let B be current (source or intermediate node) node, and A be one of its candidate forwarding nodes (only neighbors closer to destination are considered), $|BA|=r$ and $|AD|=s$. B will select one of its neighbors A which will minimize $p(B,A)=u(r)+v(s)$. The algorithm proceeds until the destination is reached, or no closer node to destination exists.

Pure power consumption metric may be misguided in the long term [SWR]: Some nodes participate in routing packets for many source-destination pairs, and the increased energy consumption may result in their failure. A longer path that passes through nodes that have plenty of energy may be a better solution, if the primary goal is to maximize the number of routing tasks the network can perform, that is, network life. The algorithm [SWR] proposed to use a function $f(A)$ to denote node A's reluctance to forward packets, and to choose a path that minimizes the sum of $f(A)$ for nodes on the path. This shortest cost path routing protocol [SWR] addresses the issue of energy critical nodes. As a particular choice for f, [SWR] proposes $f(A)=1/g(A)$ where $g(A)$ denotes the remaining lifetime ($g(A)$ is normalized to be in the interval [0,1]). Thus reluctance grows significantly when lifetime approaches 0.

The localized *cost efficient routing algorithm* [SL] can be described as follows. If destination is one of neighbors of node B currently holding the packet then the packet will be delivered to D. Otherwise, B will select one of its neighbors A which will minimize $c(A)=f(A)(1+s/R)$. The algorithm proceeds until the destination is reached, if possible, or until a node fails to find better forwarding neighbor than previous node on the path.

Power and cost are combined into a single metrics in order to choose power efficient paths among cost optimal ones. Longer paths via nodes with lot of energy will reduce a lot of power to the overall network. All proposed combinations [CT, GCNB, SL2] are variations of the product of power and cost metrics ([SL] also proposed a linear combination of two metrics, and showed it was competitive with product combination). Chang and Tassilulas [CT] applied distributed non-localized Bellman-Ford shortest weighted path algorithm. [GCNB] proposed a multi-path route-redirect algorithm, where messages are redirected through any intermediate node that saves power or reduces cost. However, multi-path transmission in effect increases the power and cost, contrary to the design goals.

Li, Aslam and Rus [LAR] discussed online power-aware routing in large wireless ad hoc networks for applications where the message sequence is not known. The goal is to optimize the lifetime of the network. They showed that online power aware routing (where incoming routing tasks are not known) does not have a constant competitive ratio to the off-line optimal algorithm (which is aware of all routing tasks). They developed an approximation algorithm that has a good competitive ratio, and selects the path with maximal minimal fraction of remaining power after the message is transmitted. The metrics used to measure that fraction is equivalent to power-cost metrics. The algorithm repeatedly calls Dijkstra's shortest path algorithm with tighter demands, removing all edges that excess preset threshold z, until source and destination are disconnected. Although the paper assumes $c=0$, it appears that the algorithm is extendable to arbitrary c in the power metric $u(d)=d^{\alpha}+c$.

Several *power-cost efficient routing* algorithms are described in [SL]. The power and/or cost aware localized algorithms are combined in [SD] with *FACE* algorithm [BMSU] (and enhanced with dominating sets and a shortcut which requires 2-hop information) to produce localized power and/or cost aware routing algorithm with guaranteed delivery.

A recent survey on power aware routing algorithms, presenting more details, is given in [LSR].

7. Hierarchical Routing

The two main strategies used to combine nodes location and hierarchical network structures are the Zone Based Routing and the Dominating Set Routing.

The *Peer-To-Peer Zone-Based Two-Level Link State Routing* [JL] and the *Online Power-Aware Routing* [LAR] schemes are example of the Zone Based Routing. In [DSW] and [SRV], as well as in *GRID* algorithm [LTS] the Dominating Set concept is introduced in routing schemes.

Joa-Ng and Lu [JL] apply the shortest path algorithm on the hierarchical graph, where a network is divided into zones. Nodes within a zone update their location between themselves regularly and apply the shortest path routes between them. Each node also records the location of each zone (by treating it as a destination node positioned in the center of that zone). Routing begins by sending the message to destination if it is in the same zone as the sender. Otherwise, the sender initiates the search for the destination by sending route requests (that is, short messages, without the actual information), one to each other zone. The zone that contains the destination (more precisely, the first node from that zone reached on the way to the center of that zone) replies with the exact coordinates of the destination back to the sender node. The sender node then learns the path to the destination (i.e. the inter-zonal path) and sends the full message (containing all the information) toward the destination, using the inter-zonal path.

Li, Aslam and Rus [LAR] considered also zone-based routing alternative of their online power aware routing algorithm [LAR]. The hosts in a zone autonomously direct local routing and participate in estimating the zone power level. Each message is routed across the zones using information about the zone power estimates. In their vision, a global controller for message routing manages the zones. This may be the node with highest power, or round robin can be employed.

A *dominating set* is set of nodes so that each node is either in the set or a neighbor of node from the set. The nodes belonging to dominating sets are called internal nodes or gateway nodes. Several localized connected dominating set definitions are given in [WL]. A node that does not have two unconnected neighbors is not in dominating set. Node *A* that has a neighbor *B* such that any path *EAF* can be replaced by the path *EBF*, and *B* has higher *ID* than *A*, can also be removed from dominating set. Finally, node *A* can be removed if it has two neighbors *B* and *C* such that any path *EAF* can be replaced by either path *EBCF* or *ECBF*, and *B* has lowest *ID* among the three, then *B* can be removed from the dominating set (but, in this case, the length of route may sometimes increase). Nodes in a dominating set are referred to as *gateway* nodes. The size of the dominating set is reduced in [SSZ] by replacing the *ID* with the *key (degree, ID)*. That way, the nodes with more neighbors have priority in entering dominating sets. Each node may decide whether or not it is in dominating set without any message exchanged with neighbors for that purpose. It suffices that each node knows its own location and location of all its neighbors (if location service is not available, then 2-hop neighboring information suffices). In order to decide which of neighbors are in dominating set, each node needs to know 2-hop information, or, alternatively, each node needs to add just one bit (referring to dominating status) in any message announcing its location to all its neighbors. In a dominating set based routing, if source is non-gateway node then it forwards message to the best gateway node neighbor, which routes the message toward *D* by considering only gateway nodes for forwarding. The message is delivered to if *D* when message reaches a gateway node neighbor of *D* for the first time. Such dominating set based routing was considered in [WL] to reduce the size of routing tables in non-position based routing algorithms.

In order to reduce the length of route discovery path (which appears to be significant) in *DFS* and position based routing algorithm, [SRV] proposed to apply dominating set concept. The application of dominating set has considerably reduced the length of discovery route, as reported in [SRV]. The lengths of QoS paths constructed by *DFS* are close to the optimal length created by the shortest path algorithm.

GFG routing algorithm [BMSU] has been improved in [DSW] by applying dominating nodes concept. While dominating sets did not improve the performance of greedy algorithm, they proved beneficial for the face mode of algorithm [BMSU] by reducing the search space for face routing (thus shortening paths and providing energy savings). Another improvement made in [DSW] is the introduction of a shortcut procedure, which requires 2-hop neighborhood information. Instead of forwarding message directly to the next node *B* by current node *A* in face mode, *A* calculates few more hops in advance, if face mode is to be applied, until the next hop is to be made to a 2-hop neighbor *C* of *A* which is not any longer direct neighbor of *A* (thus further path calculation is no longer possible). The message then does not follow the calculated path, and can be forwarded directly from *A* to *C*, thus making a shortcut. Dominating set based routing was also applied in [SD] to reduce power consumption and extend network life. These two improvements resulted in reducing the hop count, in excess of shortest path hop count, in about half for all densities.

Since network life is an important consideration, nodes in dominating sets perform more tasks and therefore reduce their remaining energy faster than other nodes. In order to address this issue, [WGS] suggested power aware dominating set definition. In this definition, each node has a key *(power level, degree, id)* for deciding dominating set status. Thus nodes use their power levels as the primary criterion, such that nodes with more power are preferred in the dominating set. If power levels are same, degrees are used as secondary key, and finally node *ID* to break ties. The further improvement is proposed in [STW], where the primary key is a linear combination of power level and degree, that is $a*power\_level + b*degree$, where a and b are parameters whose best values are to be experimentally determined and discussed in the ongoing work [STW].

Dominating set concept was often used by authors without directly refereeing to it. For instance, the backbone consisting of clusterheads and border nodes (connecting two clusters) was applied in several non-position based routing algorithms (references are given in [WL]). The maintenance of cluster structure, however, is nontrivial, since local moves may easily trigger global nontrivial updates (see [WL, SSZ]).

Another example of applying dominating set concept is ***GRID*** routing algorithm proposed by Liao, Tseng and Sheu [LTS]. The geographic area is partitioned into a number of squares called grids. In each grid, one mobile host (if any) will be elected as the leader of the grid. Routing is then performed in a grid-by-grid manner through grid leaders, and non-leaders have no such responsibility. The size *d* of each grid depends on transmission radius *R*, and several options are proposed, with general idea of one leader being able to communicate directly with leaders in neighboring grids, and all nodes within each grid being connected to their leaders. Therefore, grid leaders form a dominating set. As discussed below, similar grid construction was rediscovered in [XHE] for scheduling node sleep periods. When a leader moves, another leader from the same grid replaces it by a handoff procedure. Routing tables contain grid *ID*s instead of host *ID*s. The authors use *LAR* [KV] protocol for route discovery, although much better options are available, as already discussed in this survey. The use of *LAR* in *GRID* does not route discovery, has excessive flooding rate, and may create loops. The authors [LTS] do not elaborate on route maintenance required when a grid remains empty after its leader and only node leaves it.

8. Other Relevant Issues in Routing

The experimental design to evaluate routing schemes has some issues that required clarification. There was a tendency in early papers on position based routing (following similar research on non-position based schemes) to compare hop count in proposed schemes against flooding instead of the shortest path [KV], and to ignore flooding rate [BCSW, KV]. Also, transmission radius was used as independent variable, hiding graph density. Good results in many experiments were obtained by varying transmission range so that obtained graphs were all sparse or all dense, whichever way better results emerged. The average degree was proposed in [MC] as independent variable, and was first applied in [SL1] in experimenting with position based routing schemes. To generate random unit graphs, each of n nodes is initially chosen by selecting its x and y coordinates at random in an interval $[0,m)$. In order to control the initial average node degree k (that is, the average number of neighbors), all $n(n-1)/2$ (potential) edges in the network are sorted by their length, in increasing order. The radius R that corresponds to chosen value of k is equal to the length of $nk/2$-th edge in the sorted order [SL1]. The parameter m is used in power aware routing, and can be fixed if hop count metric is used.

The network organization problem in wireless ad hoc and sensor networks received growing attention recently. Bluetooth is am emerging standard for short range wireless communication and networking. According to the standard, when two Bluetooth devices discover each other, one of them assumes the role of master and the other becomes slave. A master with up to seven slaves defines a piconet (each node is master for only one such piconet). Collection of piconets defines scatternet. The problem of scatternet formation to enable Bluetooth-based ad hoc networks was investigated recently [LSW].

Ad hoc routing requires that nodes cooperate to forward each others' packets through the network. This means that throughput available to each single node's applications is limited not only by the raw channel capacity, but also by the forwarding load imposed by distant nodes. This effect could seriously limit the usefulness of ad hoc routing. Gupta and Kumar [GK] estimated per node capacity in ad hoc network. If node density is constant and route length grows as O($\sqrt{n}$), where n is the number of nodes in the network, then end to end throughput available to each node is O(1/$\sqrt{n}$). Thus it approaches zero as the number of nodes increases. On the other hand, if average hop count does not increase with network size (that is, most communication remains local), per node throughput remains constant.

IEEE 802.11 defines two primary modes of operation for a wireless network interface: idle state and sleep state. A node in idle state is active, and can react to ongoing traffic by switching to receive or transmit mode. A node in sleep state, however, cannot be activated by neighbors, and can return to idle state only on its own, based on preset timer. Feeney and Nillson [FN] and MIT researchers [SCIMSWC] concluded that the idle power consumption is nearly as large as that of receiving data. Nodes in ad hoc network spend about 20% more energy when receiving than when idle, and about 60% more energy in transmit than in idle mode. The error margin here is not small, as exact number depends on the equipment and defers in published articles, but rounded numbers given here are sufficient for problem description. A node in idle mode spends about 15-30 times more energy than if it is in sleep mode. Therefore it is most important to have as many as possible sleeping nodes in the network. The active nodes should be connected and should provide basic routing and broadcasting functionalities. The problem of designing sleep period schedules for each node in a localized manner was recently considered [CJBM, XNE]. [XNE] divides the sensor network area into small squares with side lengths $r=R/\sqrt{5}$, where R is the transmission radius, which ensures that two nodes which are in the same of two neighboring squares are connected. One node in each square is in idle mode, the others are in sleep mode. The idea is similar to one used in *GRID* routing algorithm [LTS]. If each node has lifetime of L time units, the algorithm is expected to extend network life to approximately Ln/M, where m is number of cells and n is number of nodes in the network (under uniform random node distribution). The *SPAN* algorithm [CJBM] selects some nodes as coordinators. These nodes form dominating set. A node becomes coordinator if it discovers that two of its neighbors cannot communicate with each other directly or through one or two existing coordinators. This is essentially the definition of dominating sets proposed in [WL]. The difference is that new and existing coordinators are not necessarily neighbors in [CJBM], which, in effect, makes the design less energy efficient because of need to maintain the positions two or three hop neighbors in complicated *SPAN* algorithm. A simplified algorithm, which applies localized power aware dominating sets defined in [WGS], is proposed in [STW].

9. *Conclusion*

Table 1 presents the summary and taxonomy of known position based routing algorithms. The successful design of localized single-path loop-free algorithms with guaranteed delivery is 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. Since the battery power is not expected to increase significantly in the future and the ad hoc networks, on the other hand, are booming, power aware routing schemes need further investigation.

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, in our knowledge, limited to [SRV], and will receive more attention in the future, since surveyed routing schemes which guarantee delivery are all very recent (except, of course, flooding).

Method	Loop-Free	Distributed	Path Strategy	Metrics	Memory	Guar.Del.	Scalability	Robustnes
shortest path [BCS, SWR]	yes	global	single-path	hop count	no	yes	no	no
greedy [F], MFR [TK]	yes[SL2]	localized	single-path	hop count	no	no	yes	no
compass [KSU]	no [SL2]	localized	single-path	hop count	no	no	yes	no
2-hop greedy [SL2]	yes	2-localized	single-path	hop count	no	no	yes	no
LAR [KV], DREAM [BCSW]	no [SL2]	localized	flooding	hop count	yes	no	no	no
V-GEDIR, CH-MFR [SL2]	yes	localized	flooding	hop count	yes	no	no	no
f-GEDIR, f-MFR [SL2]	yes	localized	single/flooding	hop count	yes	yes	Y/N dense/sparse	no
component [LS]	yes	localized	single/multi	hop count	yes	yes	yes non-sparse	no
{alternate, disjoint} greedy [LS]	yes	localized	single-path	hop count	yes	no	yes	no
c-{greedy,alternate,disjoint}[LS]	yes	localized	multi-path	hop count	yes	no	yes	no
GRA[JPS], gatewayDFS[SRV]	yes	localized	single-path	hop count	yes	yes	yes	no
zone based 2-level [JL]	yes	zonal	single/flooding	hop count	no	yes	no	no
GRID [LTS]	yes	localized	single	hop count	yes	no	no	no
shortest power path [E, RM]	yes	global	single-path	power	no	yes	no	no
cluster power [HCB]	yes	global	single-path	power	no	no	no	no
shortest cost path [SWR]	yes	global	single-path	cost	no	yes	no	no
shortest power-cost path [CT]	yes	global	single-path	power-cost	no	yes	no	no
route-redirect [GCNB]	yes	global	multi-path	power-cost	no	no	no	no
max-min zP_min [LAR]	yes	global	single-path	power-cost	no	yes	no	no
zone based max-min [LAR]	yes	zonal	single-path	power-cost	no	yes	no	no
power aware [SL]	yes	localized	single-path	power	no	no	yes	no
power-face-power [SD]	yes	localized	single-path	power	no	yes	yes	no
cost aware [SL]	yes	localized	single-path	cost	no	no	yes	no
cost-face-cost [SD]	yes	localized	single-path	cost	no	yes	yes	no
power-cost aware [SL]	yes	localized	single-path	power-cost	no	no	yes	no
Pc-F-Pc [SD]	yes	localized	single-path	power-cost	no	yes	yes	no
face, GFG [BMSU]	yes	localized	single-path	hop count	no	yes	yes	no
internal-shortcut-GFG [DSW]	yes	2-localized	single-path	hop count	no	yes	yes	no
robust GFG [BFNO]	yes	localized	single-path	hop count	no	yes	yes	yes
Terminode Routing [BGL]	yes	localized	multi-path	hop count	no	yes	yes	yes

Table 1. A taxonomy of position based routing algorithms for wireless networks

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. One of the future goals in designing routing algorithms is adding congestion considerations, that is, replacing hop count performance measure by end-to-end delay. Algorithms need to take into account the congestion in neighboring nodes in routing decisions.

Finally, the mobility caused loop needs to be further investigated and solutions to be found and incorporated to position based routing schemes.

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