Power and cost aware localized routing with guaranteed delivery in wireless networks

Ivan Stojmenovic and Susanta Datta
Computer Science, SITE, University of Ottawa, Ottawa, Ontario K1N 6N5, Canada
ivan@site.uottawa.ca

Abstract

In a localized routing algorithm, each node currently holding message makes routing decision solely based on the information about itself, its neighbors and destination. In a unit graph, two nodes can communicate if and only if the distance between them is no more than the transmission radius, which is the same for each node. A localized routing algorithm that guarantees delivery in connected unit graphs has been described recently. Also, several power, cost and power-cost aware metrics and localized loop-free routing algorithms for wireless networks based on the exact power needed for transmission between two nodes, and/or remaining battery power at nodes were proposed. However, these algorithms did not guaranty the delivery of a message in connected unit graphs. This paper proposes such localized routing algorithms, aimed at minimizing total power for routing a message, or maximizing the total number of routing tasks that a network can perform before a partition. The algorithms are combinations of known greedy power and/or cost aware localized routing algorithms and an algorithm that guarantees delivery. A shortcut procedure is introduced in later algorithm to enhance its performance. The efficiency of proposed algorithms is verified experimentally by comparing their power savings, and the numbers of routing tasks a network can perform before a node looses all its energy, with the corresponding shortest weighted path algorithms, and localized algorithms that use fixed transmission power at each node. Significant energy savings (which depend mainly on network density and maximum transmission radius) are obtained.

Index terms: Routing, wireless networks, distributed algorithms, power management

1. Introduction

In this paper we consider the routing task, in which a message is to be sent from a source node to a destination node (in a sensor, rooftop or ad hoc wireless network). Due to propagation path loss, the transmission radii are limited. Thus, routes between two hosts in the network may consist of hops through other hosts in the network. The nodes in the network may be static (e.g. sensors thrown from an aircraft to a remote terrain or a toxic environment), static most of the time (e.g. books, projectors, furniture) or moving (vehicles, people, small robotic devices). 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, HKB, KKP]. A similar wireless network that received significant attention in recent years is ad hoc network [IETF, MC]. Mobile ad hoc networks consist of wireless hosts that communicate with each other in the absence of a fixed infrastructure. Some examples of the possible uses of ad hoc networking include soldiers on the battlefield, emergency disaster relief personnel, and networks of laptops. A recent comprehensive survey of ad hoc networks is given in [G]. 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 offered by traditional telecommunication providers. 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.

Macker and Corson [MC] listed qualitative and quantitative independent metrics for judging the performance of routing protocols. Desirable qualitative properties [MC] include: distributed operation, loop-freedom, demand-based operation and 'sleep' period operation, while hop count and delivery rates are among quantitative metrics. We shall further elaborate on these properties and metrics, in order to address the issue of routing in wireless networks while trying to minimize the energy consumption and/or reduce the demands on nodes that have significantly depleted batteries. This is an important problem since battery power at each node is limited. Our final goal is to design routing protocols with the following properties.

a) Minimize energy required per routing task. 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]. The distance between neighboring nodes can be estimated on the basis of incoming signal strengths (if some control messages are sent using fixed power). 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. We will use location information in making routing decisions as well, to minimize energy per routing task.

b) *Loop-freedom*. The proposed routing protocols should be inherently loop-free, to avoid timeout or memorizing past traffic as cumbersome exit strategies.

c) *Maximize the number of routing tasks that network can perform*. 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 [SWR]. A longer path that passes through nodes that have plenty of energy may be a better solution [SWR]. Alternatively, some nodes in the sensor or ad hoc network may be temporarily inactive, and power consumption metric may be applied on active nodes.

d) *Minimize communication overhead.* Due to limited battery power, the communication overhead must be minimized if number of routing tasks is to be maximized. 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).

e) *Avoid memorizing past traffic or route*. 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). Flexibility in selecting routes is thus preferred.

f) *Localized algorithms*. 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. If an algorithm requires global knowledge, regularly maintained, at each node, the communication overhead increases quadratically with number of nodes and linearly with mobility rate. Even if network is static, global knowledge on nodes in sleep mode is still required. A worst case scenario is the need for dying node to inform the whole network (in a non-localized approach) about its disappearance, causing further energy damages. Therefore non-localized routing algorithms are not scalable. All non-localized routing algorithms proposed in literature are variations of shortest weighted path algorithm (e.g. [CN, LL, RM, SWR]).

While neighboring nodes may update each other location whenever an edge is broken or created (as discussed in [S]), the accuracy of destination location is a serious problem. In some cases, such as monitoring environment by sensor networks, the destination is a fixed node known to all nodes (i.e. monitoring center). Our proposed algorithms are directly applicable in such environments. The ultimate goal of a routing algorithm is to handle node mobility with proper *location update schemes.* This issue seems to be the most complex of all discussed here, as argued in an upcoming book chapter [S]. In this paper, we deal with location update issue in two ways.

First, our simulation assumes that accurate destination information was made available to sender node. Such an assumption is also made in MOBICOM 2000 paper [KK], which leaves incorporation of the presented routing algorithm with guaranteed delivery (originally described in [BMSU]) with location update scheme in another MOBICOM 2000 paper [LJCKM] (similar scheme was also suggested in [APL]) for future work (similar indication was given in [LJCKM]).

Second, the accurate destination information can be made by a simple (but, of course, not necessarily optimal) variant of source-initiated on-demand routing strategy [BMJHJ, RT], as follows. In this strategy, the source or intermediate node *S* issues destination search request, if route to destination *D* is not available. The destination search is performed by flooding a 'short' search message, so that each node in the network is reached. Flooding algorithms that reduce the number of retransmissions are surveyed and improved in [SSZ] for one-to-all broadcasting model, and in [SSS] for one-to-one model (in this model, each node receives messages on its own frequency, or directional antennas are used so that only selected neighbor receives message sent on common frequency). In our variant, destination routes short message to the source, using a routing algorithm with guaranteed delivery, informing the sender about its own address, thus avoiding path memorization used in [BMJHJ, JM, P, RS, RT]. Alternative (proactive) location update schemes include: doubling circles or squares [APL, LJCKM], quorum based location update [S2], home agent based [S, BBCGHL], and request zone based [BCSV, KV, S]. Our adopted reactive flooding based destination search model allows to algorithmically separate the mobility issue from the routing issue. This does not imply independence in performance measures, since mobility rate does impact significantly delivery rate (the network does not remain connected, and our guaranteed delivery refers only to connected nodes) and the number of routing tasks a network can perform.

g) *Single-path routing algorithms.* The task of finding and maintaining routes in mobile networks is nontrivial since host mobility causes frequent unpredictable topological changes. Most previously proposed position based routing algorithms (e.g. [BCSW, KV]) for wireless ad hoc networks were based on forwarding the actual message along multiple paths toward an area where destination is hopefully located, hoping to achieve robustness. However, we have shown in our previous work that single-path strategies may be even more robust (for instance, they can guarantee delivery [BMSU]) and with less communication overhead.

h) *Guaranteed delivery.* The proposed localized power and cost aware routing algorithms [SL2] achieve a very high delivery rates for dense networks, but low delivery rate for sparse networks. In this paper, we have designed power, cost, and power-cost routing algorithms that guarantee delivery, for arbitrary unit connected graph and accurate destination information. The corresponding power and/or cost non-aware routing algorithms are given in [BMSU, DSW], with a survey given in [U].

As in all cited papers, we also adopt the *unit* graph model of wireless networks as follows. All nodes have equal transmission radius R. Two nodes A and B in the network are neighbors (and thus joined by an edge) if and only if the Euclidean distance between them is less than R. The unit graph is a valid model for wireless networks whenever there are no obstacles in the signal path. Ad hoc and sensor networks with obstacles can be modeled by subgraphs of unit graphs. The properties of power metrics, the proposed algorithms and their loop free properties in this paper are valid for arbitrary graphs. The guaranteed delivery property, however, is valid only for nodes in a plane and no obstacles between them.

A number of protocols for achieving efficient routing have been recently proposed. The surveys of these protocols, that do not use geographic location in the routing decisions, are given in [BMJHJ, IETF, RS, RT]. The power awareness in these protocols is limited to the amount of control messages sent and degree of message flooding. 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 MAC protocols and routing algorithms [SWR, SL2].

In the next section, we shall review known power aware metrics and routing algorithms. Section 3 describes existing dominating sets and internal node notions that will be used in this paper. In section 4, existing routing protocol that guarantees delivery [BMSU, DSW] is reviewed. Section 5 proposes three localized loop-free algorithms that guarantee delivery and are aimed at extending node and/or network life. Their performance evaluation is given in sections 6 and 7.

2. Existing power aware metrics and routing algorithms

In most of routing protocols the paths are computed based on minimizing hop count or delay. When transmission power of nodes is adjustable, hop count may be replaced by power consumption metric. 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 [SWR]. A survey of power optimization techniques for routing protocols in wireless networks is given in [LSR].

Rodoplu and Meng [RM] proposed a general model in which the power consumption between two nodes at distance d is $u(d)=d^{\alpha}+c$ 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. In their experiments, they adopted the model with $u(d)= d^4+2*10^8$, which will be referred to as *RM-model.* They discuss that large-scale variations (modeled by lognormal shadowing model) can be incorporated into the path loss formula, and that small-scale variations (modeled by a Rayleigh distribution) may be handled by diversity techniques and combiners at the physical layer. Rodoplu and Meng [RM] described a power aware routing algorithm which runs in two phases. In the first phase, each node searches for its neighbors and selects these neighbors for which direct transmission requires less power than if an intermediate node is used to retransmit the message. This defines so called *enclosure* graph. In the second phase, each possible destination runs distributed loop-free variant of non-localized Bellman-Ford shortest path algorithm and computes shortest path for each possible source. The same algorithm is run from each possible destination. The algorithm is thus proactive, resulting in significant overhead for low data traffic volumes.

In the simple radio model [HCB], radio dissipates E_{elec}=50 nJ/bit to run the transceiver circuitry. Both sender and receiver node consume E_{elec} to transmit one bit between them. Assuming d^2 energy loss, where d is the distance between nodes, transmit amplifier at the sender node consumes further $E_{amp}d^2$, where E_{amp} = 100 pJ/bit/m^2. Thus, to transmit one bit message at distance d, the radio expends $E_{elec} + E_{amp}d^2$, and to receive the message, the radio expends E_{elec}. In order to normalize the constants, divide both expressions by E_{amp}, so that radio expands $T=E + d^2$ for transmission and $P=E$ for reception, where $E= E_{elec} /E_{amp}$=500 m^2. Note that $T/P= 1+ d^2/E$ and $T+P=2E+ d^2$. Therefore, in this model, referred to as *HCB-model,* the power needed for transmission and reception at distance d is $u(d)= 2E+ d^2$.

Stojmenovic and Lin [SL2] assumed that the power needed for the transmission and reception of a signal is $u(d)=ad^\alpha+c$. Constant factor c in this expression for total energy consumption may also include the energy consumed in computer processing and encoding/decoding at each station. Next, the leading coefficient a can be adjusted to the physical environment, unit of length considered, unit size of a signal (a bit, byte, or frame, for example) etc. In the *RM-model* $\alpha=4, a=1, c=2*10^8$, while in the *HCB-model* $\alpha=2, a=1, c=2E$. These two models were used in our experiments.

Suppose that the sender S is able to transmit the packet directly to the destination D. The following theorem determines whether energy can be saved by sending the packet to an intermediate node A between the nodes and forwarding the packet from A to D. Let $|SD|=d$, $|SA|=x$, $|AD|=d-x$. Such a node of course may not exist, but the routing algorithm will be based on proximity of existing nodes to such an intermediate node.

Theorem 1 [SL1]. 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 (that is, when $d > (c/(a(1-2^{1-\alpha})))^{1/\alpha}$), $n-1$ equally spaced nodes can be selected for retransmissions, where $n= d(a(\alpha-1)/c)^{1/\alpha}$ (rounded to the nearest integer), producing minimal power consumption of about $v(d)= dc(a(\alpha-1)/c)^{1/\alpha} + da(a(\alpha-1)/c)^{(1-\alpha)/\alpha}$.

Theorem 1 announces the possibility of converting polynomial function in d (with exponent α) for power consumption (in case of direct transmission from sender to destination) to linear function in d by retransmitting the packet via some intermediate nodes that might be available.

If nodes have information about position and activity of all other nodes then optimal power saving algorithm, that will minimize the total energy per packet, can be obtained by applying Dijkstra's single source shortest weighted path algorithm, where each edge has weight $u(d)=ad^\alpha +c$, where d is the length of the edge. This will be referred as the *SP-power algorithm.*

The corresponding loop-free localized power efficient routing algorithm can be described as follows [SL2]. The source (or an intermediate node) B should select one of its neighbors to forward packet toward destination, with the goal of reducing the total power needed for the packet transmission. In this and other localized algorithms described in this section, only neighbors that are closer to destination than B are considered (if no such node exists, routing fails). Let A be a neighbor of B, and let $r=|AB|$, $d=|BD|$, $s=|AD|$. The power needed for transmission from B to A is $u(r)=ar^\alpha +c$, while the power needed for the rest of routing algorithm is not known. Assuming uniformly distributed network, a fair assumption that the power consumption for the rest of routing algorithm is equal to the optimal one is made (see Theorem 1). That is, the power needed for transmitting message from A to D is estimated to be $v(s)= sc(a(\alpha-1)/c)^{1/\alpha} + sa(a(\alpha-1)/c)^{(1-\alpha)/\alpha}$. For $\alpha=2$, $v(s)=2s(ac)^{1/2}$. This is, of course, an unrealistic assumption. However, it is fair to all nodes. We experimented also with formula $tv(S)$, and optimal values for t appear to be between 1 and 2, with no clear winner for all the method. We shall use value $t=1$ in the sequel. Node B will select one of its neighbors A which will minimize $p(B,A)=u(r)+v(s)= ar^{\alpha}+c + sc(a(\alpha-1)/c)^{1/\alpha} + sa(a(\alpha-1)/c)^{(1-\alpha)/\alpha}$. For $\alpha=2$ it becomes $u(r)+v(s)= ar^2 +c + 2s(ac)^{1/2}$. If destination D is a neighbor of B then compare the expression with the corresponding one, $u(d)=ad^{\alpha}+c$, needed for direct transmission ($s=0$ for D, and D can be treated as any other neighbor). The algorithm proceeds until the destination is reached, if possible.

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 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 other metric used in [SWR] is aimed at minimizing the total energy consumed per packet. However, [SWR] merely observes that the routes selected when using this metric will be identical to routes selected by shortest hop count routing, since the energy consumed in transmitting (and receiving) one packet over one hop is considered *constant*. For each of the two proposed power consumption metrics (cost and hop count), [SWR] assigns weights to nodes or edges, and then refers to non-localized Dijkstra's algorithm for computing shortest weighted path between source and destination. It is referred to as the *SP-cost* algorithm in experimental data in this paper. The algorithm uses the cost to select the path, but the actual power is charged to nodes. We also observed that the validation of power aware metrics in [SWR] was done on random graphs where each pair of nodes is joined by an edge with a fixed probability p.

The localized version of *SP-cost* algorithm [SWR] algorithm, assuming constant power for each transmission, can be designed as follows [SL2]. The cost $c(A)$ of a route from B to D via neighboring node A is the sum of the cost $f(A) =1/g(A)$ of node A and the estimated cost of route from A to D. The cost $f(A)$ of each neighbor A of node B currently holding the packet is known to B. In [SL2], the cost of remaining path is assumed to be proportional to the number of hops between A and D. The number of hops, in turn, is proportional to the distance $s=|AD|$, and inversely proportional to radius R. Thus the cost is ts/R, where factor t is to be investigated separately. We selected $t= f(A)$ (best performing definition from [SL2]). The cost $c(A)$ of a route from S to D via A is then estimated to be $c(A)=f(A)+ts/R$. 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 $c(A)$. The algorithm proceeds until the destination is reached, if possible, or a node has no closer node to destination than itself.

Chang and Tassiulas [CT1, CT2] and Stojmenovic and Lin [SL2] (technical report published in 1998) independently proposed combining power and cost into a single metric. In [CT1] Chang and Tassiulas experimented with metric $c_{ij}=(\underline{E}_i-e_{ij}\lambda)^{-1}$, where $e_{ij}=u(d)=d^4+c$ is energy for transmission on link ij with length d, λ and c are small constants, and $\underline{E}_i$ is remaining battery power at node i. In [CT2] they proposed a general metric $c_{ij}=e_{ij}^{a}\underline{E}_i^{-b}E_i^{c}$, where E_i is initial energy at node i, and a , b and c are constants. They consider routing tasks with fixed source-destination pairs, one-to-one [CT1] and one-to-many [CT2] cases. The power needed for reception is not considered. Distributed non-localized Bellman-Ford shortest weighted path algorithm is used. Their experiments indicate *(a,b,c)=(1,50,50)* as values that are close to optimal one. Network lifetime is maximized when traffic is balanced among the nodes in proportion to their energy reserves, instead of routing to minimize the absolute consumed power [CT1, CT2]. A similar power-cost metric was proposed also in [GCNB], followed by 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.

Stojmenovic and Lin [SL2] proposed two different ways to combine power and cost metrics into a single power-cost metric, based on the product and sum of two metrics, respectively. If the product is used, then the power-cost of sending message from B to a neighbor A is equal to $power\text{-}cost(B,A)=f(A)u(r)$ (where $|AB|=r$). The sum, on the other hand, leads to a new metrics $power\text{-}cost(B,A)=\alpha u(r) + \beta f(A)$, for suitably selected values of α and β. For example, sender node S may fix $\alpha=f'(S)$ and $\beta=u(r')$, where r' is the average length of all edges going out of S. The values α and β are (in this version) determined by S and used, without change, by other nodes B on the same route. The corresponding shortest path algorithms can find the optimal power-cost by applying single source shortest weighted path Dijkstra's algorithm (the node cost is transferred to the edge leading to the node). The product version (called *SP-Power*Cost)* performed better in [SL2] for the shortest power-cost path, and is selected for this paper for the comparison.

The *power-cost efficient routing* algorithm may be described as follows [SL2]. Let A be the neighbor of B (node currently holding the message) that minimizes $pc(B,A)= power\text{-}cost(B,A) + v(s)f'(A)$ (where $s=0$ for D, if D is a neighbor of B). The variant $power\text{-}cost(B,A)= f'(S)u(r)+u(r')f(A)$ performed better in experiments [SL2], is loop-free [SL2] and was thus selected in this paper for localized algorithm. The packet is delivered to A. Thus the packet is not necessarily delivered to D, when D is a neighbor of B.

3. Dominating sets and internal nodes

A set is dominating if all the nodes in G are either in the set or neighbors of nodes in the set. Nodes that belong to a dominating set will be called, in this paper, internal nodes for G. Routing based on a connected dominating set is frequently used approach [WL], where the searching space for a route is reduced to corresponding internal nodes. The routing process, in this approach, is divided into three steps. If source node is not an internal node, it forwards the packets to one of its adjacent internal nodes. This internal node then acts as a new source to route the packets in the reduced graph consisting of internal nodes only. Eventually, the packets reach the destination internal node, which is either the destination node itself or neighbor of the destination node. In the later case, the destination internal node forwards the packets directly to the destination node. Such routing is suggested for the shortest path [WL], for DSR (dynamic source routing) [WL], and for localized routing with guaranteed delivery [DSW].

Wu and Li [WL] proposed a simple and efficient distributed algorithm for calculating connected dominating sets in ad hoc wireless networks, modeled by arbitrary graphs. They introduced the concept of an *intermediate* node. A is an *intermediate* node if and only if there exist two neighbors of A that are not direct neighbors themselves. If location information (that is, geographic position) of nodes is not known to nodes then the list of 2-hop neighbors (that is, neighbors of each neighbor) suffices to make such decision at each node (if these lists are exchanges between neighboring nodes). On the other hand, if nodes know the location of all its neighbors, and G is unit graph with a given radius R known to all nodes, then each node can determine whether or not it is an intermediate node without any message exchanged with its neighbors for that purpose.

Wu and Li [WL] introduced also two rules that considerably reduce the number of internal nodes in the network, and proved that these rules preserve network connectivity after eliminating additional nodes from the dominating set. Let *N(u)* be the (open) set of all neighbors of node *u,* and let $N[u]=N(u) \cup \{u\}$ be the corresponding closed neighbor set, that is the set of all neighbors and *u* itself. Suppose that each node has a unique *id* number (it may be obtained by generating a random number in [0,1], or their *x*-coordinate may serve the purpose). Let us define *inter-gateway* nodes as nodes intermediate nodes that are not eliminated by Rule 1. Rule 2 will not be used here since experiments in [DSW] did not offer any advantage in using that rule. Rule 1 [WL] is as follows.

Consider two intermediate nodes *v* and *u*. If $N[v] \subseteq N[u]$ in *G* and $id(v) < id(u)$, then node *v* is not an inter-gateway node. In other words, if any neighbor of *v* is also a neighbor of *u,* and *v* is connected to *u* and has lower *id,* then any path via *v* can be replaced by a path via *u,* thus node *v* is not needed as internal node. We may also say that node *v* is 'covered' by node *u.* Observe that the hop count between any two nodes does not increase by applying Rule 1, since a segment *pvq* of a path between source and destination is replaced by a segment *puq,* thus hop count does not change. Since routing on inter-gateway nodes performed better than routing on intermediate nodes in [DSW], this paper adopts inter-gateway node definition in experiments involving internal nodes.

Stojmenovic, Seddigh and Zunic [SSZ] proposed to replace node *id*s with a record (*degree, x, y*), where *degree* is the number of neighbors of a node, and *x* and *y* are its two coordinates in the plane (if available, otherwise they may use a random number instead). In Rule 1, nodes compare first their degrees, and node with higher degree has greater chances of remaining an internal node. In case of ties, use *x*-coordinates as secondary and *y*-coordinates as ternary keys. The information about the degree of neighboring nodes may be gathered together with information about their location. Such definition is used in broadcasting algorithm (where a message is to be sent from one node to all other nodes in the network) [SSZ], where only internal nodes retransmit the message, resulting in reduction in retransmissions to roughly half of nodes compared to flooding method where all nodes retransmit.

4. Existing localized routing algorithm which guarantees delivery

Bose, Morin, Stojmenovic and Urrutia [BMSU] described a GPS based localized routing algorithm which guarantees the delivery for wireless networks modeled by unit graphs, assuming only that the graph is connected. The only additional constraint is, of course, that the position of destination (as recorded by the sender node) is reasonably accurate. Let *G* be the graph, containing *n* vertices, that corresponds to the wireless network. Since *G* is unit graph, there exists radius *R* such that two vertices are connected in *G* if and only if the distance between them is $<R$.

The algorithms works as follows. In the first phase, construct planar connected subgraph *P* of *G*. *P* is the intersection of unit graph and Gabriel graph *GG* on the set *S* of *n* given nodes, defined as follows. Let *disk(u,v)* be the disk with diameter *(u,v).* Then, the Gabriel graph *GG(S)* is a graph in which edge *(u,v)* is present if and only if *disk(u,v)* contains no other points of *S*. *GG(S)* is a planar graph (that is, no two edges cross each other). It was proved in [BMSU] that the intersection of connected unit graph and Gabriel graph is a connected planar graph. The planar subgraph is constructed in localized manner. More precisely, each node needs to know only the location of its neighbors, and does not need any additional communication step to decide, for each of its edges, whether it belongs to *P*. Let *A* be one of nodes, and *B* one of its neighbors. Edge *AB* belongs to *P* if and only if $|CM|<|AB|/2$ for each neighboring node C of A, where M is the middle point between A and B. Alternative criterion is the following: an edge AB is included in the subgraph if and only if $\angle ACB$ is acute, for each joint neighbor C of A and B. Therefore, the construction of $GG(S)$ does not require any message exchange between neighboring nodes, other than regular location updates.

In the second phase, a path between source node S and destination node D in P is constructed. Planar subgraph P divides the plane into several faces. One of them is open (or infinite) while other faces are closed. The straight line segment between S and D intersects several faces of P, in a particular order. Any edge of P belongs to exactly two faces. The message traverses these faces, one by one, and changes from a face to the next face at the edges that intersect line SD. Details of this algorithm, called *FACE,* are given in [BMSU, DSW]. The paths generated by *FACE* algorithm are considerably long. However, nodes do not need to memorize past traffic in order to forward the message correctly. Also, there is no need for multiple paths. That is, at each step there is exactly one copy of the message in the network. The *FACE* algorithm may be used in practice in combination with an algorithm that performs well whenever it does not fail, such as greedy routing scheme [F]. [BMSU] proposed an algorithm that begins routing with greedy scheme until message is delivered, or fails at a node C. The failure node is defined as node C that has no closer neighbor to D than itself. Such choice node enables to prove that the combined algorithm remains loop-free, and guarantees delivery. At C, *FACE* algorithm is invoked which guarantees delivery. The algorithm is further improved, by proposing *GFG* (Greedy-FACE-Greedy) routing scheme. In this scheme, routing follows greedy method until a node C is reached that has no neighbor closer to destination than itself. The distance $d=|CD|$ is attached to the message, and C invokes *FACE* algorithm which runs until message is delivered, or a node B such that $|BD|<d$ is found. Routing then continues again with greedy until message delivery of the next node C that has no closer neighbor to destination. Thus the number of switches from greedy to *FACE* and back may be arbitrary, but each switching node is closer to destination than the previous one. The performance evaluation in [BMSU] confirm that *GFG* method is very practical, and in case of low degree graphs with few hundred nodes it generates paths which are on average up to 3.5 times longer than paths generated by shortest path (*SP*) algorithm. In case of high degree networks, the performance of *GFG* is very close to the performance of *SP* algorithm.

Karp and Kung [KK] implemented *GFG* algorithm [BMSU] by adding a full IEEE 802.11 MAC protocol, and by experimenting with mobile nodes moving according to a random waypoint model, using ns-2 environment. They used the same simulation code as the measurement study used to evaluate DSR protocol [BMJHJ]. Accurate destination information was used in [KK], thus location updates and corresponding overhead were not implemented or measured. Their *GPSR* (Greedy Perimeter Stateless Routing) algorithm, extended from *GFG*, consistently delivered over 94% (mobility may introduce disconnection) data packets successfully; it is competitive with *DSR* in this respect on 50 node networks at all pause times, 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 [KK] with over 100 nodes. Therefore the scalability seems to be the major advantage of *GFG* algorithm over existing well known protocols.

Datta, Stojmenovic and Wu [DSW] proposed to restrict *GFG* algorithm on the set of internal nodes only, and to shorten paths in *FACE* mode by a shortcut procedure, as follows. One of main problems with *FACE* algorithm, causing its increased hop count, is that the planar subgraph construction phase favors short edges over long ones. A route between source and destination is therefore likely to contain a number of short edges. This means that a node *A* in the path might have, in addition to forwarding node, few more nodes in the same path as its neighbors. If node *A* receives the information about each neighbor of each of its neighbors, it can accurately construct the local portion of path in *FACE* algorithm, and select the furthest known node on the path to send the message directly to it, thus making a shortcut. Note that *A* can predict next hops even if face is changed in the process. In order to apply the shortcut procedure, neighboring nodes need to exchange the list and location of their neighbors, in addition to their own location, whenever a change in local topology occurs. In other words, 2-hop local information is needed. The experiments in [DSW] indicate that the overhead, in excess of the shortest path algorithm, can be reduced to about half of the overhead in [BMSU] for any graph density.

5. Power and cost aware routing algorithms with guaranteed delivery

In this section we describe our localized power and/or cost aware routing algorithms which guaranty delivery in connected unit graphs. The algorithms are combination of power, cost, or power-cost routing algorithm (respectively) with the *FACE* algorithm, similarly as greedy algorithm is combined with *FACE* to define *GFG* algorithm. We shall call these algorithm *PFP, CFC,* and *PcFPc* algorithms, respectively.

More precisely, routing begins with *P* (power), *C* (cost), or power-cost (*Pc*) scheme (respectively) until message is delivered, or fails at a node *C*. The failure node is defined as node *C* which has no closer neighbor to *D* than itself. Such choice node enables to prove that the combined algorithm remains loop-free, and guarantees delivery. The distance $d=|CD|$ is attached to the message, and *C* invokes *FACE* algorithm which runs until message is delivered, or a node *B* which has a neighbor *B'* such that $|B'D|<d$ is found. The message is sent to the best such neighbor *B'* (if any, and according to considered criterion), and routing then continues again from *B'* with corresponding *P, C* or *Pc* method, until message delivery or the next node *C* that has no closer neighbor to destination is encountered. Thus the number of switches from *P, C,* or *Pc* method to *FACE* and back may be arbitrary, but each switching node is closer to destination than the previous one. This property, together with the guaranteed delivery property of *FACE* algorithm, suffices to claim guaranteed delivery property for *PFP, CFC,* and *PcFPc* algorithms, and consequently their loop-freedom.

One possible enhancement of each algorithm is to restrict them to internal nodes only. Our experiments showed that internal node concept showed no significant improvement (or drawback) in hop count, delivery rates or power savings when applied in conjunction with greedy power/cost aware or non-aware algorithms. However, notable improvement was obtained when concept was applied in *FACE* mode of routing algorithm. By reducing the number of nodes to internal node set, *FACE* algorithm is applied on smaller set, therefore producing shorter paths in its maze like traversal of faces on route from source to destination.

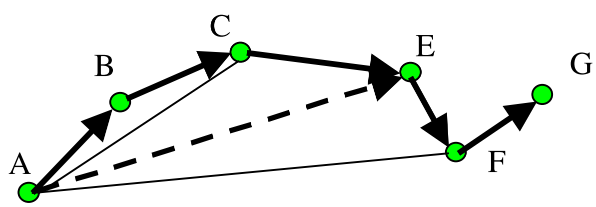

Figure 1. Path ABCE replaced by AE in the shortcut procedure

The second improvement is to adjust shortcut procedure [DSW] so that the best neighbor in each case, in *FACE* mode, is selected. Consider, for example, the path *ABCEFG* in Fig. 1, where *B, C, E* and *F* are neighbors of A. Node *A* is normally neighbor for several subsequent nodes in *FACE* algorithm, since the later favors 'short' edges. Knowing the neighbors of each neighbor, node *A* may determine this path and send message directly to some other node instead to neighbor *B* determined by *FACE* algorithm. Using appropriate criteria for each of power, cost, and power-cost routing algorithms, node *A* selects the best neighbor, say *E,* and forwards the message directly to *E,* thus deleting nodes *B* and *C* from the path. If power aware routing algorithm is considered, the best neighbor is one that minimizes $u(|AX|)+tv(|XD|)$, where *X* is *B, C, E* or *F*.

If cost aware routing is considered, then *A* may send message directly to *F,* furthest known node on the path, since the cost of other intermediate nodes is avoided in this way. However, if the cost of node *F* is high, this may not be the best solution. Node *E,* having much lower cost, and knowing more subsequent nodes on the path than node *A*, might be in position to avoid *F* later, and therefore reduce overall cost. Other alternative is to select node, say *E,* which has lowest cost among *B, C, E* and *F*. This also may not be best choice, since the node may not advance sufficiently toward destination. Thus we propose to use cost $c(X)$ as defined above, which is the sum of cost of *X* and estimated cost of remaining path, which depends on distance to destination. In case of power-cost algorithm, the function $pc(A,X)$, explained above, may be similarly applied.

7. Performance evaluation of power efficient routing algorithm

The experiments are carried on both static and mobile networks. Each of n nodes is initially chosen by selecting its x and y coordinates at random in the interval $[0,m)$. In order to control the initial average node degree k (that is, the average number of neighbors), we sort all $n(n-1)/2$ (potential) edges in the network 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. The experiments with static networks required connected unit graphs. The experiments on moving nodes were carried as follows. Each node moves according to the following mobility pattern. It chooses a random destination and random number *mov-it*, the number of steps (iterations) it will take to reach the destination, from a given interval [*min-mov-it, max-mov-it*]. When node reaches its destination, it makes a new selection of *mov-it* and random destination and repeats the process. One routing task per iteration is performed in the network, by choosing source and destination nodes at random. MAC layer was not implemented, so possible collisions of location update and routing traffic are assumed to be handled by either acknowledgements within IEEE 802.11 or by time division multiple access in multi-hop ad hoc networks (see a recent survey [L]). Because of using single path strategy and one routing task at a time, there would be no collision within routing traffic even if a MAC layer were added. By choosing *mov-it* parameter, node in effect chooses its speed. We assumed that the speed of performing routing task is significantly greater than the node movement. The size of iteration should be chosen such that each node performs very few, if any, location update activities during the iteration. Disconnected source-destination pairs are detected by repeating the same edge on *FACE* path twice (such pairs are also confirmed by running shortest path algorithm on the same pairs). Each node sends location update message to all its neighbors whenever it detects that an existing link is broken, or a message from a new neighbor is heard. It was observed that the failure rate due to using imprecise neighborhood information is far below 1%, and that mobility had no significant negative impact on routing process. This is similar conclusion to one reported in [KK]. The measured data for static and moving networks did not differ significantly. We have therefore chosen to present data only for static networks. The average number of location update messages per node was also measured. It grows with mobility and network density but was constant with respect to number of nodes in the network, thus confirming scalability, which *DSR* and other non-position based routing protocols are lacking [KK]. The primary goal of this paper and experimental design was to show power savings and network's life extension for new protocols while preserving guaranteed delivery property, compared to algorithm [BMSU, DSW], and to confirm that savings are stable with respect to node mobility. Note that the number of routing tasks that a network can perform is negatively impacted by node mobility because of communication overhead imposed by location updates.

We have experimented with number of nodes from $n=40$ to $n=100$, and average node degrees from k=3 to k=10. We compared all methods for squares of sizes m=10, 100, 200, 500, 1000, 2000, 5000 for both *HCB*- and *RM-models*. The results are averages over 20 graphs with 100 routing pairs in each chosen at random. We considered two different models in our experiments. The first model is the one described in literature review (and used by other authors), where transmission power is charged to sender node (and depends on distance between nodes), and a fixed power for reception is charged to receiving node. In that model, energy $d^{\alpha}+E/2$ is charged to transmitting node, while the receiving node is charged with the remaining power $E/2$. The presented data refer to this model. This model is justified if neighboring nodes that are not message receivers can temporarily switch to sleep mode after realizing that they are not intended receivers. Otherwise, each neighboring node shall be charged for listening to the message. We have designed the following model for this case. Assume that a node choose the transmission power according to a neighbor that is at distance d. The power needed for another neighbor at distance r to receive the message is $q(Ed^{\alpha}/(r^{\alpha}+E) + E^2/(r^{\alpha}+E))=a(r)d^{\alpha}+c(r)$, where q is a constant whose value is between 0.1 and 1 (the value $q=1$ corresponds to the case when reception power for node at distance $r=0$ from sender is the same as transmission power; such model follows from [RM, HCB]). Let a and b be the summations of $a(r)$ and $c(r)$ over all neighbors (and possibly even all nodes in the network, if the energy for receiving noise is also to be charged). We conclude that the overall energy charged to the network is again of the form $ar^{\alpha}+c$; however constant a and c differ at each node. Thus the localized algorithm remains the same under this model, and the performance evaluation gives, surprisingly, similar conclusion. We therefore did not include experimental results for this model in the paper.

Degree	4	5	6	7	8	9	10
FACE-I	8765	8015	8191	7015	7057	7394	7662
FACE-I-S	5206	4821	5014	4474	4647	4961	5520
GFG -I	4276	3858	3884	3464	3546	3747	4064
GFG-I-S	3861	3684	3700	3438	3529	3715	4057
PFP	4717	3985	3815	2936	2921	3080	3032
PFP-S	4050	3659	3485	2807	2800	2909	2930
PFP-I	4216	3670	3681	2992	2956	3148	3177
PFP-I-S	3783	3437	3380	2883	2845	3008	3075
PFP-I-S-2t	3671	3387	3344	3023	2855	2973	3029
SP-POWER	2886	2913	2879	2548	2541	2592	2670

Table 1: Power Consumption per one routing task for n=40 nodes and m=1000

Table 1 presents the average power consumption per successful routing task in networks with n=40 nodes placed in a square of size m=1000 and average degrees from 4 to 10. The results for other values of *n* were similar. The suffix 'I' denotes the application of inter-gateway node concept, while suffix 'S' denotes the application of shortcut procedure. The data for *SP-power* method are optimal power consumption, received by applying Dijkstra's shortest weighted path algorithm. The advantage of using shortcut procedure is notable, giving more benefits overall than the inter-gateway node concept. The overall efficiency of localized power efficient algorithm with guaranteed delivery is notable. The excess power needed for delivery for best *PFP-I-S* method ranges from 31% for degree d=4 (which frequently calls *FACE* algorithm) to 15% for d=10 which rarely calls *FACE* procedure. Power savings obtained by applying power formula, measured in terms in excess power over minimal one required by *SP-power* algorithm are also notable. For instance, *PFP-I-S* over *GFG-I-S* has savings ranging from about 10% for d=4 to about 30% for d=10. Power formulas use value $t=1$ in $u(r)+tv(s)$, except the method *PFP-I-S-2t* in Table 1 that used value $t=2$. This was the largest overall difference in results for different values of t.

8. Performance evaluation of cost and power-cost efficient routing algorithms

The experiments that evaluate cost and power-cost routing algorithms are designed as follows. Random unit connected graphs are generated as in the previous section. An iteration is a routing task specified by the random choice of source and destination nodes. A power failure occurs if a node has insufficient remaining power to send a message according to given method. Iterations are run until the first power failure at a node occurs (at which point the corresponding method 'dies'). Each node is initially assigned an energy level at random in the interval [*minpow, maxpow*], where parameters depend on *m*. After sending a message from node *A* to node *B,* the energy that remained at *A* (*B*) is reduced by the power needed to transmit (receive) the message, respectively. The experiment is performed on 20 graphs for each method, for each of *HCB*- and *RM-model* formulas.

Degree	4	5	6	7	8	9	10
Face2-I	152	176	160	180	167	177	150
Face2-I-S	157	188	172	200	197	211	180
GFG	193	212	181	252	234	238	218
GFG-S	194	213	182	252	234	238	218
GFG-I	189	213	182	230	240	226	198
GFG-I-S	191	215	183	229	241	226	198
PFP	222	258	222	304	330	313	290
PFP-S	226	265	223	307	329	317	280
PFP-I	210	252	214	281	312	284	271
PFP-I-S	215	259	216	291	313	299	278
CFC	202	254	228	322	364	360	372
CFC-S	203	254	229	324	363	365	376
CFC-I	205	260	222	313	361	343	356
CFC-I-S	206	261	224	314	363	345	355
PCFPC	226	282	251	354	377	373	370
PCFPC-S	224	288	253	360	385	383	387
PCFPC-I	223	283	251	349	372	380	367
PCFPC-I-S	224	292	256	352	377	383	390
SP	218	242	196	248	252	238	210
SP-Power	252	294	229	316	342	333	307
SP-Cost	237	297	258	380	376	365	370
SP-Power*Cost	262	329	278	438	425	427	426

Table 2. The number of iterations for n=40, m=100, and power interval [3M,4M]

Table 2 presents experimental data on the number of routing tasks a network can perform before a first node dies, for network with n=40 nodes placed in a square of size m=1000, average degrees from 4 to 10, and with initial nodes power selected at random in interval [3000000, 4000000]. Quadratic formula for power was used, while power-cost formula for localized algorithm is discussed in section 2. Note that shortest weighted path algorithms used are not necessarily optimal, and that our localized algorithms are very competitive with them. It can be observed that power-cost combination is better than power or cost alone. Also, our power, cost and power-cost aware routing algorithms were superior in these experiments with respect to non-power or non-cost aware localized algorithms, and superiority increased with degree. Power aware algorithm *PFP+* extended network life 13%-40% over corresponding non-power aware *GFG+* algorithm, cost aware formula *CFC+* extended 8%-80% over *PFP+,* and power-cost aware *PcFPc+* extended 17%-97% over *GFG+* ('+' refers to same extension in both names). Compared to best shortest weighted path *SP-Power*Cost* algorithm, our best performing localised algorithm *PcFPc-I-S* achieve 83%-92% of network life. Therefore although the performance did not seem much improved for lower degrees, it appears that no significant improvements are possible either since *PcFPc-I-S* is close to performance of *SP-Power*Cost* for all degrees.

Conclusion

This paper described several localized routing algorithms that try to minimize the total energy per packet and/or maximize lifetime of the network and guaranty delivery for unit graph model of wireless networks. The proposed routing algorithms are all demand-based and can be augmented with some of the location update schemes, reported in literature, that will supply the reasonably accurate destination information to sender node. These methods use control messages to update positions of all nodes to maintain efficiency of routing algorithms. However, these control messages also consume power, and the best trade-off for moving nodes is to be established. Therefore further research is needed to select the best protocols. Our primary interest in this paper was to examine power consumption with respect to power non-aware protocols and provide basis for further study. Power efficient methods tend to select well positioned neighboring nodes in forwarding the message, while cost efficient method favor nodes with more remaining power. The node movement, in this respect, will certainly assist power aspect of the formula since the movement will cause the change in relative node positioning. This will further emphasize the advantage of power-cost over power only or cost only methods.

Interestingly, the performance of internal node based routing also improves with mobility (if the cost of location updates is ignored), since mobility changes frequently the dominating set. When the nodes are static, the fixed choice of internal nodes becomes routing bottleneck, since these nodes are used more often than others in routing messages. To address this problem, [WGS] proposed a different definition of dominating sets, the one that takes remaining power at nodes into account when deciding internal nodes. Thus the dominating set will change for static networks by applying this definition. The incorporation of this new definition into our protocols is left for future study.

The formulas for power, cost, and power-cost methods may also need some improvements. Our experiments do not give an ultimate answer on even the selection of approach that would give the most prolonged life to each node in the network. We will investigate this question further in our future work which will consider a number of metrics including generalized one $f(A)^a u(r)^b$, which is similar to one proposed in [CT2].

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