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Location-based localized alternate, disjoint and multi-path routing algorithms for wireless networks

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Abstract

Recently, several fully distributed (localized) location-based routing protocols for a mobile ad hoc network were reported in literature. They are variations of directional (*DIR*), geographic distance (*GEDIR*) or progress-based (*MFR*) routing methods. In *DIR* methods, each node *A* (the source or intermediate node) transmits a message *m* to several neighbors whose direction is closest to the direction of *D*. In *MFR* (most forward progress within radius), and *GEDIR* (GEographic DIstance Routing) methods, when node *A* wants to send *m* to node *D*, it forwards *m* to its neighbor *C* whose projection or distance (respectively) is closest to *D* among all neighbors of *A*. The same procedure is repeated until *D*, if possible, is eventually reached. In this paper, we introduce three variants of multiple path *c-GEDIR*, *c-DIR* and *c-MFR* methods, in which *m* is initially sent to *c* best neighbors according to corresponding criterion, and afterwards, on intermediate nodes, it is forwarded to only the best neighbor. In the *original c-path* method, only the first received copy at intermediate nodes is forwarded to the best neighbor. In the *alternate c-path* method, the *i*th received copy is forwarded to *i*th best neighbor, according to the selected criterion. In the *disjoint c-path* method, each intermediate node, upon receiving the message, will forward it to its best neighbor among those who never received the message (thus, in effect, the methods attempts to create *c* disjoint paths). The simulation experiments with random graphs show that disjoint multiple path methods provide high success rates, and small hop counts for small values of *c*. They also have reduced flooding rates compared to the best existing multiple-path methods and/or methods that require memorizing past traffic, such as recently proposed *LAR2*, *f-GEDIR*, and *DFS* based routing, and can serve as a basis for scalable QoS routing in wireless networks.

Keywords: Routing; Wireless networks; Distributed algorithms; Mobile computing; Shortest path

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 given wireless 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]. 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

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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.

A broad variety of location-dependent services will become feasible in the near future due to the use of the Global Position System (GPS), which provides location information (latitude, longitude and possibly height) and global timing to mobile users. GPS cards will be deployed in each car and possibly in every user terminal. If GPS is not available, 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]. This paper will make use of geographic position of nodes in making routing decisions.

Routes between two hosts in a wireless network may consist of hops through other hosts in the network. The task of finding and maintaining routes in a wireless network with moving nodes is non-trivial since host mobility causes frequent unpredictable topological changes. A number of protocols for achieving efficient routing have been recently proposed. A number of novel routing protocols are also available on the internet [IETF]. In this article we will discuss only position-based approaches (their survey is given in [U]).

This paper is organized as follows. Section 2 lists desirable properties of a routing protocol for ad hoc networks. Section 3 reviews existing location-based routing methods, while Sections 4 and 5 describe new alternate, disjoint, and multi-path routing methods. The multi-path methods are compared with the best existing multi-path methods and/or methods that require nodes to memorize past traffic, *LAR2*, *f-GEDIR*, and *DFS* based routing in Section 6. Conclusion and references complete this paper.

2. Desirable properties of routing protocols for ad hoc networks

Ad hoc networks consist of autonomous nodes that run their routines in asynchronous fashion. The communication algorithms between nodes are therefore all distributed. However, [EGHK] defined the class of *localized* algorithms, as distributed algorithms where simple local node behavior achieves a desired global objective. Localized algorithms therefore resemble greedy sequential algorithms. In a localized routing algorithm, each node makes the decision to which neighbor(s) to forward the message based solely on the location of itself, its neighboring nodes, and destination. In addition, each node is allowed to perform local computation.

Non-localized algorithms, on the other hand, typically require the knowledge of the locations of all nodes in the network, and also the information about the existence of every edge in the graph. All non-localized routing algorithms proposed in literature are variations of shortest weighted path algorithm. Although ad hoc networks are fairly accurately modeled by *unit* graphs (where two nodes A and B in the network are neighbors if and only if the Euclidean distance between them is less than R, where R is the transmission radius that is equal for all nodes), nodes that are at distance less than R may have an obstacle between them blocking the communication, while two nodes at distance that exceeds R by a small amount may still be able to communicate (or a node may even choose whether to use that possible but power demanding link). The maintenance of shortest weighted path requires that information about edges, in addition to location of nodes, is broadcast to the whole network, which is a significant quadratic communication overhead, and may cause significant delays in delivery. Next, some nodes in the sensor or ad hoc network may be temporarily inactive, and non-localized algorithms need to know which of the nodes are active to make their best decisions. The activity information puts additional demand on the information update. For example, static nodes may need to broadcast such information to the whole network whenever they change their activity status while, at the same time, they have no need to update their location with the rest of the nodes. In order to preserve battery power over long periods of time, nodes may change their activity on a regular basis. Even worse scenario is a need for dying node to inform the whole network (in a non-localized approach) about its disappearance, causing further energy damages. Thus, non-localized shortest path algorithms may not be the best choice for a routing algorithm even in case of static networks (e.g. some kinds of sensor networks). This paper deals solely with localized algorithms.

Macker and Corson [MC] listed qualitative and quantitative independent metrics for judging the performance of 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). It was shown in [SL1] that existing directional-based solutions [BCSW,KV,KSU] are not loop-free, while *MFR* algorithm [TK] and *greedy* and similar *GEDIR* algorithms [F,SL1] are loop-free.

Some quantitative metrics that are appropriate for assessing the performance of any routing protocol include [MC]: end-to-end data delay, and average number of data bits (or control bits) transmitted per data bits delivered. The later is a measure of communication overhead, and includes demand-based routing messages and location updates.

Delivery rate [BMJHJ] is the ratio of numbers of messages received by destination and sent by senders. Despite high communication overhead (due to flooding an area toward destination), existing directional-based methods [BCSW,KV] report only 80–90% delivery rates. Our goal is to design multi-path routing algorithms with high delivery rate and low communication overhead, achieved by restricted flooding approach.

The design of a routing algorithm for mobile wireless networks appears to be a very difficult problem, as argued in a recent book chapter [S1]. One possible approach [KV,KK,SL1,SL,SRV] is to limit location updates to neighboring nodes only, and use a variant of reactive source initiated destination search routing [BMJHJ], where routing is divided into three steps as follows: destination search with short messages (using multi-path strategies or flooding), routing from destination to sender (that is, reporting the position), and finally sending full message from source to destination. This strategy is adopted in previous research [KK,KV], and is suitable for quality-of-service routing. It works well with our proposed multi-path schemes, and was also used in *LAR2* scheme [KV] and *f-GEDIR* [SL1] that were used for comparison in this paper. Other possible approaches [BCSW,S1] are more proactive, with some mobility-dependent location updates. Note that 'intelligent' flooding schemes, which reduce the number of message retransmission yet preserving reachability, are discussed in [SSZ,SSS].

Multi-path schemes are well known in wired networks. They are captured in a link state routing protocol in Internet called OSPF [Mo] by the notion of 'equal cost multi-path', where traffic should be split equally between all the equal cost paths. They were proposed for non-location-based routing in wireless networks in [Le,RG,NCD,VG,ZG] and are used in traffic load balancing, for minimizing delay, and for QoS routing. In these methods, the second path is selected at the destination node among successful routes. In these schemes, route discovery is followed by selecting two or more paths from destination to source, among those found in the search process. The second path is maximally disjoint with the first one, and can serve for backup routing or splitting the traffic. We note that the whole path must arrive to destination node (so that destination may determine disjoint paths), thus message length increases with each hop, and the solution is not scalable. Moreover, if the second path is not fully disjoint with the first one, only the disjoint portion of the two paths from the last common node of two paths to the destination may arrive at destination, since intermediate nodes normally forward only the first copy of route discovery message. Therefore the second path from source to the last common node is canceled by the last common node, and destination is not aware of it. Wu [W] introduced a different approach. The two paths are created during route discovery process, by using two colors to divide all nodes into two disjoint sets, and find one route to destination in each of the set. Each node colors itself after receiving a message from one or both routes. In our proposed (scalable) location-based localized multi-path algorithm (which was first reported in our technical report [SL-tr] in 1998), the sender may initialize c paths toward destination, to provide multiple paths with controlled communication overhead. In these methods, past traffic at each node needs to be memorized (however, only message *id* is memorized), which applies also to the directional algorithms [BCSW,KV], *LAR2* [KV], *f-GEDIR* [SL1], and *DFS* based routing [SRV].

Currently, one of main directions in ad hoc research is scalability. Routing algorithms should perform well for wireless networks with arbitrary number of nodes. To achieve scalability, we replace existing $O(n)$ average (*LAR2*) or worst-case (*f-GEDIR*) multi-path routing algorithms with an $O(\sqrt{n})$ algorithm, where n is the number of nodes in the network, and the measure refers to the expected number of nodes in the network receiving routing packet. Algorithms [BCSW,KV] apply multi-path strategies with linear communication overhead, and are not scalable.

3. Known location-based routing methods

Several GPS-based methods were proposed in 1984–86 by using the notion of progress. Define progress as the distance between the transmitting node and receiving node projected onto a line drawn from transmitter toward the final destination. 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). In the random progress

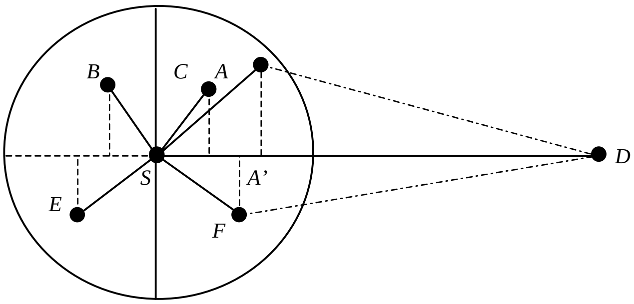

Fig. 1. Progress based routing methods.

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.

Takagi and Kleinrock [TK] proposed *MFR* routing algorithm, in which packet is sent to the neighbor with the greatest progress (e.g. node A in Fig. 1). We shall reformulate the *MFR* method in order to facilitate its implementation. Let $a \cdot b$ denote the dot products of vectors a and b. Consider the dot products of vectors originating from destination D and ending at nodes in the network. Clearly $DS \cdot DA = |DS||DA'|$ where A' is the projection of A on the line DA (see Fig. 1). The sign is assumed here to be positive; it can be shown that, in case of negative dot product, D must be a neighbor of S. Thus the considered dot product is minimal exactly when the progress in maximal. The goal in the *MFR* algorithm [TK] is, therefore, to minimize the dot product. Note that the node that minimizes the dot product (the selected node) may not have a forward progress. The *MFR* algorithm is loop-free [SL1].

Recently, three articles [BCSW,KV,KSU] independently reported variations of fully distributed routing protocols based on direction of destination. In these directional routing methods, node A uses the location information for B and its one hop neighbors to obtain B's direction, and then transmits a message m to several neighbors whose direction (looking from A) is closest to the direction of D. The methods differ in the choice of direction ranges.

In the *compass routing* method (referred here also as the *DIR* method) proposed by Kranakis et al. [KSU], the source or intermediate node A uses the location information for the destination D to calculate its direction. The location of one hop neighbors of A is used to determine for which of them, say C, is the direction AC closest to the direction of AD (that is, the angle CAD is minimized). The message m is forwarded to C. This process repeats until the destination is, hopefully, reached. Basagni et al. [BCSW] described a distance routing effect algorithm for mobility (DREAM). The source or any intermediate node A calculates the direction of destination D and, based on the mobility information about D, chooses an angular range. The message m is forwarded to all neighbors whose direction belongs to the selected range. The range is 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. The area containing the circle and two tangents is referred as the request zone in [KV]. DREAM algorithm [BCSW] incorporates the idea of triggering the sending of location updates by the moving nodes autonomously at a rate and hop distance that correspond to the node's mobility rate. Ko and Vaidya [KV] described, independently at the same conference, two very similar algorithms, and a few modifications of them. In the location-aided routing (*LAR*) algorithm [KV], the request zone is fixed from the source, and a node which is not in the request zone does not forward a route request to its neighbors. If the source has no neighbors within the request zone, the zone is expanded to include some. The size of the request zone depends on the average speed of the destination's movement and time elapsed since the last known location of the destination was recorded [BCSW,KV].

The definition of the request zone [BCSW,KV] was modified in [S2] in order to provide uniform framework with the corresponding notions in *GEDIR* and *MFR* methods. Stojmenovic [S2] discusses the *V-GEDIR*, *CH-MFR* and *R-DIR* methods, in which m is forwarded to exactly those neighbors which may be best choices for a possible position of destination (using the appropriate criterion). The request zone in *R-DIR* method [S2] may include one or two neighbors that are outside of angular range, because they can have the closest direction for the tangents to the circle. In *V-GEDIR* method, these neighbors are determined by intersecting the Voronoi diagram of neighbors with the circle (or rectangle) of possible positions of destination, while the portion of the convex hull of neighboring nodes is analogously used in the *CH-MFR* method.

Ko and Vaidya [KV] discussed various enhancements to their basic technique. The *LAR scheme* 1 [KV] proposes an alternative definition of the request zone, as the smallest rectangle that includes current location of S and the expected zone of destination (a circular region). The request zone is thus increased, with increased chances of reaching destination but also with increased flooding. The modifications in [KV] include sending route requests before the message itself [JM]. Note that a route request may be considered as a routing of short messages. Nodes may update their location information with each exchange of messages between them. Messages may contain source location also to update location information at intermediate nodes. Recovery procedures based on partial or full flooding, to start flooding if the given algorithm fails to find the route within a timeout interval, are proposed by both papers [BCSW,KV].

Ko and Vaidya [KV] also proposed the *LAR scheme* 2. In this scheme, the source or each intermediate node A will forward the message to all nodes that are closer to the destination than A is (more precisely, at most δ farther from the destination than node A, to account for possible location error). This scheme therefore suggests the use of geographic distance instead of direction.

Simulation results presented in [BCSW] using a discrete event simulator show that the dynamic source routing protocol [JM] has a 25–250% larger end-to-end delay than the *DREAM* protocol. The average number of data bits transmitted per data bits delivered is consistently lower for both *LAR* schemes as compared to flooding [KV]. Therefore adding location information to the routing tables in all nodes resulted in significant improvement in the performance over the existing methods that do not use such information. Despite these advantages, the proposed methods [BCSW,KV] have some drawbacks. They have considerable flooding rates, and the directional methods are shown in [SL1] not to guaranty loop-free paths.

Finn [F] proposed Cartesian routing method, which allows choosing any successor node that makes progress toward the packet's destination. The best choice depends on the complete topological knowledge. Finn [F] adopted the greedy principle in his simulation: choose the successor node that is closest to the destination. When no node is closer to the destination than current node, the algorithm performs a sophisticated procedure that does not guaranty delivery. In the example in Fig. 2, sender *S* selects node *B* that is closer to *D* than *A*. The path selected by the algorithm is *SBEFGHID* and consists of seven hops. *GEDIR* routing algorithm [SL] is a variant of greedy routing algorithm [F] with a 'delayed' failure criterion. *GEDIR*, *MFR*, and compass routing algorithms fail to deliver message if the best choice for a node currently holding message is to return it to the previous node [SL1].

Stojmenovic and Lin [SL1] proposed a modification to all three basic algorithms to avoid message dropping. Each algorithm proceeds as described until the message is supposed to be dropped by the corresponding algorithm at a 'concave node' *A*. Flooding is performed only at concave nodes, while every other intermediate node should act with receiving message as in the corresponding basic routing algorithm. After forwarding the packet to all its neighbors, a concave node shall mark packet *id* in the entry corresponding to given destination, and refuse to accept the same packet from any of its neighbors. Neighbors of concave node will recognize that the message was flooded, and will ignore it when selecting future best neighbors. In effect, the concave node has disconnected itself with respect to given packet. It is not necessary to carry additional flooding bit with the packet. The delivery of the packet to the destination is guaranteed (assuming that the network is connected graph). The methods will be refereed to as *flooding GEDIR*, *flooding DIR*, and *flooding MFR* routing methods (abbreviated as *f-GEDIR*, *f-DIR* and *f-MFR*). It is straightforward to show that *f-GEDIR* and *f-MFR* methods guarantee delivery (for connected graphs without message collisions) and that they are loop-free (neither of properties is valid for *f-DIR* algorithm).

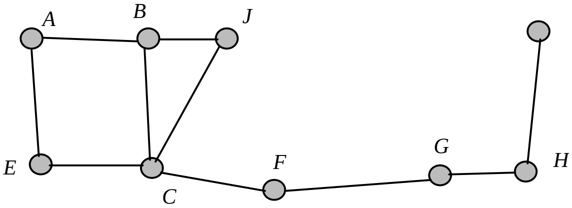

Fig. 2. Alternate *ABJBCJCFGHD* and disjoint *ABJCFGHD* paths from *A* to *D*.

A depth first search (*DFS*) based routing algorithm was proposed in [SRV]. Each node follows *DFS* in searching for destination, and orders all its neighboring nodes according to their distance from destination, the closer ones being preferred. The algorithm guarantees delivery, and nodes need to memorize past traffic (as demanded by *DFS* on arbitrary graph) but the flooding rate for sparse networks is significant, as shown in [SRV].

A *GFG* routing algorithm that guarantees delivery by finding a simple path between source and destination is described in [BMSU]. It is based on constructing a planar subgraph (e.g. Gabriel graph) and routing in the planar subgraph that guarantees delivery. This procedure is called whenever greedy algorithm fails, and is recalled whenever a closer node (than previously failing node) is encountered. *GFG* algorithm [BMSU] was implemented in [KK] by including MAC layer considerations and location updates for experiments with moving nodes. Karp and Kung [KK] also showed the scalability of the algorithm and its better performance than the well-known *DSR* algorithm [BMJHJ]. The performance of *GFG* algorithm was improved in [DSW] by adding a shortcut procedure and applying internal node concept (see [SSZ]). The hop count is very close to the hop count of shortest path algorithm for dense graphs (below 20% excess hop count for graphs with average degrees $\geqslant 6$) and about twice longer for sparse graphs. Corresponding power and cost aware routing algorithms with guaranteed delivery are developed in [SD].

Routing protocols related to GPS, and using congestion control, which forces routing messages to follow different path, if the node is congested, have been studied in [BFD,BDF].

4. Alternate and disjoint routing methods

Each of proposed new schemes uses one of three basic algorithms (*GEDIR*, *MFR* or *DIR*) as its underlying algorithm for the criterion in selecting the best neighbor to forward the message. As in [SL1], it was observed that the performance of *MFR* variant is very similar to the performance of *GEDIR* variant and leads to loop-free algorithms, while performance of *DIR* variant was always somewhat worse and not loop-free. Therefore we decided to refer only to *GEDIR* in the sequel, that is, to geographic distance as the criterion in neighbor selection.

In the *original GEDIR* method [SL1], every intermediate node will forward the message to its best neighbor (the one closest to the destination). Forwarding stops if the best neighbor is the neighbor message came from, that is, at concave node. Methods differ in the way they handle concave nodes routing decisions.

In the *alternate GEDIR* algorithm, each intermediate node forwards *i*th received copy of the same message to the *i*th best (closest to destination) neighbor. Thus concave nodes of the original *GEDIR* method do not stop transmitting; however a node becomes concave if it has fewer neighbors than the number of received copies. Temporary loops may be created, but the exit is guaranteed with maximum node degree.

In the *disjoint GEDIR* method, each intermediate node A, upon receiving the message, will forward it to its best neighbor among those who never received and forwarded the same message before. After forwarding the message, node A becomes inactive with respect to that message, and rejects further copies of it. All neighbors of A receive message forwarded by A and may eliminate A from their list of candidate neighboring nodes for forwarding the same message. A node stops forwarding the message (e.g. becomes concave) if there is no neighbors left to forward the message. Loops cannot be created by the algorithm design.

Consider an example for alternate and disjoint methods in Fig. 2, for routing from A to D. In the alternate method, A sends to B, B to J, J back to B since B is best neighbors for J (note that J would be a concave node in *GEDIR*), B to the second best choice C, C to the best choice J, J to second best choice C, C to the second best choice F, F to G, G to H and H to D. In the disjoint method, A sends to B and disconnects, B sends to J and disconnects, J to C (since B is not available) and disconnects etc. until D is reached.

Fig. 3 illustrates why disjoint method is more successful than alternate one. This conclusion is also confirmed by experiments. In the alternate method, node A sends message to best neighbor node B, B back to A, A to the second best neighbor C, C to the best neighbor B, B to the second best neighbor C, and C to the second best neighbor A which is concave node for the method since it has no more neighbors. In the disjoint method, A sends to the best neighbor B and rejects further messages, B sends to the best remaining neighbor C, C sends to E since A and B are not available for the message, etc. until D.

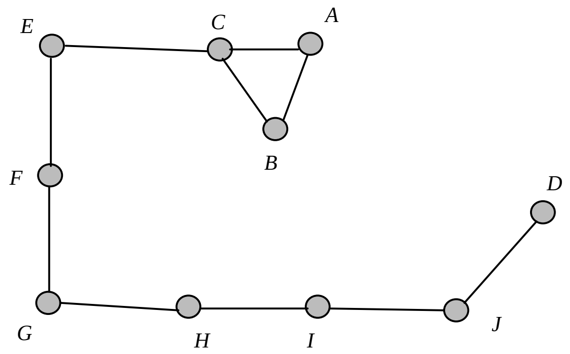

Fig. 3. Alternate *ABACBCA* and disjoint *ABCEFGHIJD* paths from *A* to *D*.

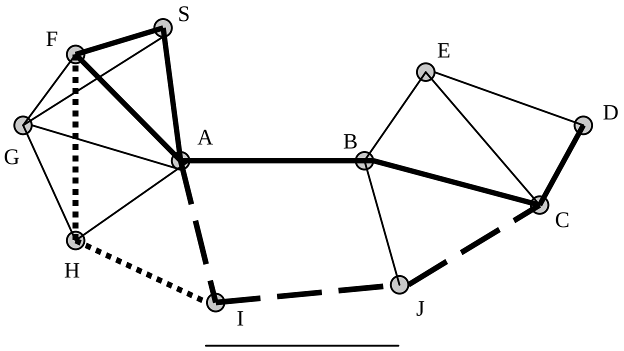

Fig. 4. The first path *SABCD* and second original (*SFA*), alternate (*SFAIJCD*), and disjoint (*SFHIJ*) paths from *S* to *D*.

5. Multi-path routing methods

In the *multi-path* method, the source node forwards the message to c best neighbors, according to selection criterion. In the *original c-GEDIR* method, each node forwards the first received copy to the neighbor that is closest to destination (or stops forwarding if the node is concave) and does not forward other received copies. In the *alternate c-GEDIR* method, intermediate nodes on each path follow the described behavior whenever they receive any copy of the message (irrelevant from which of c initiated paths the message originates). Thus *i*th received copy of the same packet is forwarded to *i*th closest to destination neighbor, up to the number of neighbors. Nodes in the *disjoint c-GEDIR* algorithm do not receive the same packet twice; thus the scheme merely attempts to create c disjoint paths between source and destination nodes. The proposed multi-path methods provide robustness without much additional flooding. In all three methods, if destination D is one of neighbors of the current node C, the message is delivered to D, which might be an exception to the corresponding behavior at C.

Consider an example in Fig. 4, where message is to be sent from S to D using $c = 2$ paths. The radius of the

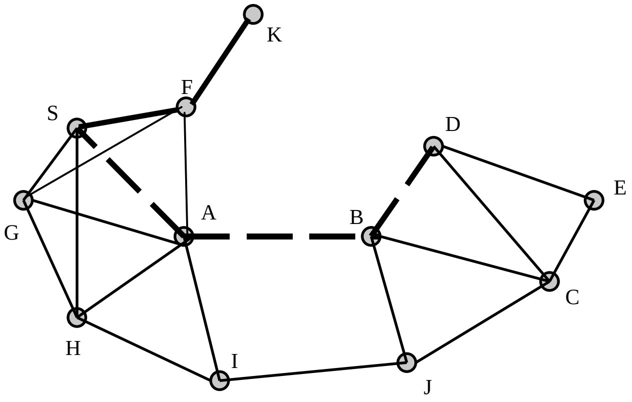

Fig. 5. The first path *SFK* fails, the second path *SABD* is successful.

unit graph is shown below the graph. The original methods produce the first successful path *SABCD*, while the second path *SFA* stops at *A*. Both paths are shown with bold lines. Two alternate paths are *SABCD* and *SFAIJCD*. New edges in alternate path are shown with dashed lines. Finally, the disjoint method produces the same first path *SABCD* while the second path, which fails, is *SFHIJ* (new edges on the path are shown with dotted lines).

Fig. 5 shows an example where the first path *SFK* from *S* to *D* fails by all three methods, while the second path *SABD* is successful and is same for all three methods.

It was observed experimentally that $c<4$ are reasonable choices for c, while the additional success rate for $c>3$ does not compensate for additional flooding rate. We note that flooding effect, or the preferred choice of parameter c, may be related to the need to construct alternative QoS routes in the network.

6. Performance evaluation

The experiments were carried out using random unit graphs, on both static and moving nodes. Each of n nodes is chosen by selecting its x and y coordinates at random in the interval $[0, 100)$. In order to control the average node degree d, 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 d is equal to the length of $(nd/2)$th edge in the sorted order. In experiments with static networks, generated graphs, which were disconnected, are ignored (connectivity cannot be preserved with mobility). We experimented with the following network sizes: $n = 20$, 50, and 100. For $n = 20$, the average degrees tested were $d = 2$, 3, 4 and 5; for $n = 50$, d ranges between 4 and 8; and for $n = 100$, d is between 4 and 14. For each graph, 50 random source–destination pairs are chosen, and the routing was performed in both directions (thus 100 routing tasks per graph). Averages over 20 graphs with the same parameters are then found. We shall present here only results for $n = 100$.

Since our final goal is to provide a localized algorithm that will compete with the shortest path algorithm, we have used, in this paper, *flooding rate* as an appropriate 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 message can be sent to all neighbors with one transmission. The *hop count* refers to the smallest number of transmissions on a route between two nodes that is established by applying particular algorithm (in other words, it corresponds to the delay in receiving the first copy of a packet). Finally, the *success* (or delivery) rate is the ratio of delivered packets.

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 (thus end-to-end data delay [MC] is replaced with *hop count* [BMJHJ]), 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]). 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. 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. Reactive flooding based destination search method, described in introduction, is used. 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. The measured data for static and moving networks did not differ significantly. We have therefore chosen to present data only for static networks. The communication overhead imposed by location updates was ignored, since it was the same for all compared schemes (it was also ignored in other relevant experiments, e.g. [KK,KV]). A recent survey [S1] discusses the issue in detail.

LAR2 scheme from [KV] is added in the experiments, since it had best performance among schemes proposed by the same authors, according to their measurements. In one transmission step (of broadcast type), the source or each intermediate node A will forward the message to all nodes that are closer to the destination than A is (thus we selected value $\delta = 0$). When a message is to be routed from source S to destination D, the nodes located inside a circle centered at assumed position of D and with radius SD might all receive the message, thus $O(n)$ nodes might be flooded. We assumed that nodes in *LAR2* do memorize messages and do not retransmit the same message more than ones. Nodes in *LAR2* which have no closer neighbor to destination than themselves do not retransmit the message. *LAR2* method did not offer reliable success at low degrees (78% for $d = 4$) while the success rate for larger d for satisfactory (95% for $d = 6$). Hop counts range from 7.5 at $d = 4$ to 5.7 at $d = 6$ to 3.9 at $d = 10$. The flooding rate of *LAR2* increased significantly with the degree (from about twice *SP* flooding at $d = 4$ and 4.3 times at $d = 6$ to >9 at $d = 10$ and about 14 at $d = 14$ or over 40% of nodes).

The second path seems to improve success rate of single path method by over 10% for low degree networks, by about 5% for medium degrees, and by 1% for high degree networks that already have very high success rates. Adding memory for past traffic to multi-path methods seems to have significant impact, especially for disjoint methods that achieve similar success rates as *LAR2* even for the single path case. It appears that the third path adds about 1% in success rate with high price in flooding rate. Adding the fourth path does not seem to give any benefit in our experiments, but 4-path method applied on $n = 100$ and $d = 6$ still has lower flooding rate than *LAR2* method, with better success rates for disjoint path version. Therefore multi-path methods provide scalability and basis for QoS routing.

We have added *f-GEDIR* scheme from [SL1], which was shown to perform better than *LAR2* for all network densities. We have also added *DFS*-based routing algorithm [SRV], which has superior performance for dense networks, but has significant flooding rate for sparse networks. Table 1 presents experimental results on delivery rates of multiple path methods for $n = 100$ and $d = 6$. The improvements obtained by adding multiple paths and/or past traffic memory are notable. The success rate increases by about 3–5% from $c = 1$ to 2, by additional 2% from $c = 2$ to 3, and by 1% from $c = 3$ to 4. Alternative methods have about 5% higher success rates than original ones for all c values. Disjoint methods have about 15–17% better success rate than the corresponding original ones, for all values of c. Similar results were obtained for $n = 100$ and $d = 4$, 5, and 7. It is worth to note that disjoint methods achieve almost same success rate as *LAR2* even at $c = 1$ value, and involve almost no unnecessary flooding. Delivery rates for *f-GEDIR* and *DFS* based routing are 100%, and they are not shown in Table 1.

Table 1
Delivery rates for multiple path methods for $n = 100$ and $d = 6$

	c Value			
	1 (%)	2 (%)	3 (%)	4 (%)
Original GEDIR	77.30	80.70	81.95	82.70
Original DIR	79.10	81.60	83.00	83.90
Original MFR	78.40	81.70	83.00	83.70
Alternate GEDIR	80.70	86.05	87.65	88.10
Alternate DIR	82.85	86.95	88.65	89.10
Alternate MFR	81.70	86.55	87.85	88.35
Disjoint GEDIR	92.10	96.20	97.55	97.80
Disjoint DIR	90.90	95.10	96.90	97.30
Disjoint MFR	92.25	96.10	97.75	98.00
LAR2	95.45			

Table 2
Delivery rates for multiple path methods for $n = 100$, $d = 4, 5, 7$ and $c = 1, 2, 3, 4$

Method	Degree	$c = 1$ (%)	$c = 2$ (%)	$c = 3$ (%)	$c = 4$ (%)
Original GEDIR	4	50	53	55	55
Alternate GEDIR	4	53	58	59	59
Disjoint GEDIR	4	69	79	82	83
Original GEDIR	5	62	66	67	68
Alternate GEDIR	5	66	71	73	73
Disjoint GEDIR	5	83	89	92	92
Original GEDIR	7	81	81	81	81
Alternate GEDIR	7	84	84	84	84
Disjoint GEDIR	7	95	97	98	98
LAR2	4	77			
LAR2	5	90			
LAR2	7	98			

Table 3
Hop counts for multiple path methods for $n = 100$ and $d = 6$

	c Value			
	1	2	3	4
SP	5.82	5.82	5.82	5.82
Original GEDIR	5.13	5.17	5.20	5.21
Original DIR	5.55	5.45	5.47	5.49
Original MFR	5.16	5.20	5.23	5.25
Alternate GEDIR	5.41	5.55	5.60	5.60
Alternate DIR	5.95	5.93	5.93	5.90
Alternate MFR	5.44	5.57	5.57	5.58
Disjoint GEDIR	6.45	6.21	6.09	6.06
Disjoint DIR	6.63	6.30	6.23	6.19
Disjoint MFR	6.35	6.13	6.09	6.05
LAR2	5.65			
f-GEDIR	7.22			
DFS	21.05			

Table 2 presents delivery rates for few more degree values, for *original*, *alternate* and *disjoint c-GEDIR* (for $c = 1, 2, 3, 4$) and *LAR2* methods. Table 3 presents hop counts for multiple path methods. Alternate methods have slight hop count increase while disjoint methods

Table 4
Flooding rates for multiple path methods for $n = 100$ and $d = 6$

	c Value			
	1	2	3	4
SP	1	1	1	1
Original GEDIR	0.83	1.19	1.43	1.62
Original DIR	0.91	1.20	1.46	1.65
Original MFR	0.84	1.21	1.46	1.65
Alternate GEDIR	1.04	2.17	3.23	4.02
Alternate DIR	1.14	2.42	3.57	4.39
Alternate MFR	1.05	2.19	3.25	4.06
Disjoint GEDIR	1.16	2.48	3.64	4.52
Disjoint DIR	1.19	2.45	3.59	4.38
Disjoint MFR	1.14	2.46	3.61	4.49
LAR2	5.20			
f-GEDIR	3.11			
DFS	3.48			

have about one extra hop, compared to original methods. This is due to increased success rate, coming from paths to destination discovered by second and later paths, when the first path failed. However, second and other paths tend to be longer than the first one, since the best looking route from the source has been reserved for failing path. Note that hop counts for *f-GEDIR* and *DFS* based routing are higher than for other considered methods, which is trade-off for guaranteed delivery. For denser graphs *f-GEDIR* and *DFS* based scheme become superior methods, while for sparser graphs multi-path methods provide better trade-off.

Table 4 gives the corresponding flooding rates, with numbers around c (that is, about c shortest paths), which is expected. The first path has roughly the length of the shortest path (or even shorter, due to increased failure rates that results in shorter paths, which do not reach destination. Two paths together are more successful, but one of them is forced to be longer than shortest path, thus flooding rates are over 2 for alternate and disjoint methods (due to lower success rates, they are below 2 for original methods). Similar analysis applies to third and fourth paths. Significantly higher flooding rates for *LAR2* method can be easily observed. The somewhat better success rate and hop count for *LAR2* are achieved with about twice larger flooding rates (for $c = 2$ and 3), which is not justified. Observe that for $c = 2$ and 3 disjoint *c-GEDIR* offers over 92% and 96% success rate, respectively, one less hop on average, and three times and 20–30% lower flooding rates compared to *f-GEDIR* and *DFS*, which is a compensation for guaranteed delivery of *f-GEDIR* and *DFS* based schemes.

In summary, multi-path methods have significantly lower flooding rates than *LAR2* at moderate and high degrees (from $d = 6$ for $n = 100$). *LAR2* has lower hop counts, but the difference is significant only for small degree networks. Thus our multi-path based methods are superior to *LAR2* for higher degree networks, while better delivery rates offer satisfactory compensation for higher flooding rate for lower degree networks.

7. Conclusion

The proposed demand-based multi-path algorithms operate in the same manner if some nodes are in the ‘sleep’ mode. The only modification is to include a condition at each node to ignore its neighbors that are temporarily not receiving messages. If nodes that are in the ‘sleep’ mode are actual destinations, the messages for them should be stored until they are ready to receive them.

Our experiments show that *c-GEDIR* and *c-MFR* may provide multiple paths with comparable success rates and much smaller flooding rates, with respect to *LAR2*. They also give high success rates with low flooding rates for low degree networks, compared to *f-GEDIR* and *DFS* based schemes, which seem to pay high price for guarantying delivery in low degree networks. Further, the performance of multi-path methods is relatively stable with respect to network density, compared to other methods.

The multi-path routing scheme proposed in this paper (and other methods considered here) can clearly be combined with a number of location update schemes in order to produce a full routing protocol. Thus one paper does not seem to be sufficient to design a routing algorithm satisfying listed desirable properties, and/or to find the best combination of basic routing scheme and location update scheme. We assumed here that weaker basic routing component would contribute to weaker overall routing protocol that handles mobility, and therefore limited our scope by considering only simple location update schemes, or even static networks in initial experiments. That allowed us to concentrate on low communication overhead of the basic routing algorithm, measured by flooding rates, and scalability, and proposed multi-path algorithms that can be used as basis for a complete routing solution in mobile wireless networks. $O(\sqrt{n})$ multi-path algorithm provides scalability and better relative performance over competitive methods for larger values of n (we have confirmed that by doing experiments with various values of n). Selecting proper value for c controls flooding rate. We concluded that values $c = 1$, 2 or 3 may be justified, based on network density, desired success level, and desired trade-off with flooding rate as overhead.

The ultimate goal is to find the best combination of basic routing and location update schemes, for which an in-depth study is necessary because of possible interactions between ingredients.

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