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Voronoi diagram and convex hull based geocasting and routing in wireless networks

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Summary

In this paper, we propose a general algorithm (based on an unified framework for both routing and geocasting problems), in which message is forwarded to exactly those neighbors which may be best choices for a possible position of destination (using the appropriate criterion). We then propose and discuss new VD-GREEDY and CH-MFR methods and define R-DIR, modified version of existing directional methods. In VD-GREEDY 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. Routing and geocasting algorithms differ only inside the circle/rectangle. The proposed methods may be also used for the destination search phase allowing the application of different routing schemes after the exact position of destination is discovered. VD-GREEDY and CH-MFR algorithms are loop free, and have smaller flooding rate (with similar success rate) compared to directional method. We proposed to use dominating set concept to reduce flooding ratio significantly, with a marginal impact on success rate and hop count. Simulations, involving the proposed and some known algorithms, are performed for two basic scenarios, one for geocasting and reactive routing, and the other for proactive routing, and both showed that our methods have higher success rate and lower flooding rate compared to existing methods. Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS: *ad hoc* wireless networks; routing; geocasting

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1. Introduction

Mobile *ad hoc* networks consist of wireless hosts that communicate with each other in the absence of a fixed infrastructure. Routing is a problem of sending a message from a source to a destination. Routes between two hosts in the network may consist of hops through other hosts in the network. The task of finding and maintaining routes in the network is nontrivial since host mobility causes frequent unpredictable topological changes. A number of network protocols for achieving efficient routing have been recently proposed. They differ in the approach used for searching a new route and/or modifying a known route, when hosts move. In this article, we will discuss only position-based approaches. Position of nodes is

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available by using a small power chip GPS receiver, or by evaluating relative positions using signal strengths or time delays.

Geocasting is the problem of sending a message to all nodes located within a region (e.g., circle or square). It is a variant of the conventional multicasting problem. Conventional protocols define a multicast group as a collection of hosts, which register to a multicast group address. However, for geocasting, the group consists of the set of all nodes within a specified geographic region. Hosts within the specified region at a given time form the geocast group at that time.

We shall adopt localized approach in our research. 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. While neighboring nodes may update each other's location whenever an edge is broken or created, the accuracy of destination location is a serious problem [1]. Based on mobility information about destination, its latest known location may not be accurate to a node wishing to route message to it. It is therefore assumed that the destination is located inside a circle or square, centered at its latest known location, whose size depends on available mobility information. In routing algorithms discussed in this paper, forwarding node makes the forwarding decision based on these data. Message may be forwarded to none, one or several neighbors. In the geocasting problem, all nodes within a circle or square are supposed to receive the message, not just its center (as in the routing problem). In the unified framework that we adopt, geocasting problem is solved by routing towards the center of the region, even though that center is not necessarily a node of the network. The equivalence is valid as long as receiving nodes are lying outside the geocasting region. However, nodes inside the region may, upon receiving the message, forward it to some additional nodes, or simply broadcast it to all its neighbors. The decision can be made independently on the routing method applied outside the region. We extend our unified framework toward unified definition of forwarding region and derive routing and geocasting algorithms for each of three basic methods reviewed in the next section. Versions that require and do not require to memorize past traffic are discussed. In References [1–4], it is suggested to solve the mobility problem by separating location update and destination search steps from the actual routing. Based on their mobility, nodes periodically update their location to their smaller or larger neighborhood. When a source wishes to send a message ('long' message) to a destination, it initiates destination search process by sending 'short' messages looking for destination. Destination, when discovered, will report back to sender with its exact location, allowing sender to send the long message to exact location of destination (possibly with a different routing method, for example, one with guaranteed delivery [5]). The geocasting algorithms, discussed in this paper, may be used for the destination search step of the algorithm instead of using them for sending the 'long' message.

Recently, several localized position-based routing and geocasting protocols for a mobile *ad hoc* network were reported in the literature. In directional (DIR) routing and geocasting methods, node *A* (the source or intermediate node) transmits a message *m* to all neighbors located between the two tangents from *A* to the region that could contain the destination. It was shown that memoryless directional methods may create loops in routing process. In two other proposed methods (proven to be loop-free), geographic distance (*greedy*) or most forward progress within radius (MFR) routing, node *A* forwards the message to its neighbor who is closest to destination, or has greatest progress toward destination (respectively). In this paper, we propose the VD-GREEDY routing method, based on determining those neighbors of current node that may be closest to a possible location of the destination. Several methods, exact and approximate, for determining such neighbors are discussed. They are based on the intersection of the Voronoi diagrams or bisectors with the circle or rectangle of possible positions of destination. The corresponding CH-MFR is also described, based on the convex hull on neighboring nodes, while the analogous *R-DIR* is modified from References [6,7]. The methods proposed here are originally described in References [1,18]. The preliminary conference version of this article appeared in Reference [9]. This version adds dominating set-based enhancement and also contains experiments with mobile nodes in proactive setting. The next section presents the survey of relevant routing algorithms and location update schemes. More detailed surveys are given in References [1,10,11].

2. Relevant Work

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. Takagi and Kleinrock

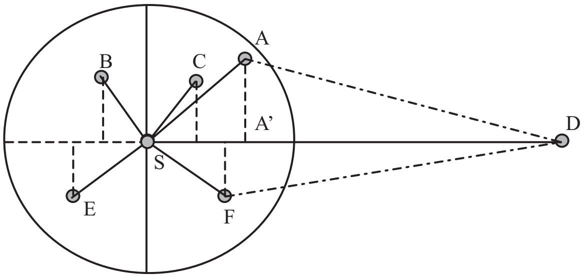

Fig. 1. The selection of the next node *A* in *MFR* and *greedy* methods, and next node *F* in the compass routing method.

[12] proposed MFR (most forward within radius) routing algorithm, in which packet is sent to the neighbor with the greatest progress. For example, current node *S* in Figure 1 has five neighbors *A, B, C, E*, and *F*, and it selects *A* since the projection A' of *A* on the line SD is closest to *D*. The routing then continues from *A* in the same fashion. The MFR algorithm is loop-free [13].

Finn [14] proposed *greedy* routing algorithm for *ad hoc* networks. When node *S* wants to send a message to destination *D*, it uses the location information for *D* and for all its one-hop neighbors to determine the neighbor *A*, which is closest to *D* among all neighbors of *S*. Figure 1 is an example where *A* is closest to *D* among all neighbors of *S*. The message is forwarded to *A*, and the same procedure is repeated until *D*, if possible, is eventually reached. GEDIR algorithm [13] is a variant of greedy algorithm with a different stoppage criterion (returning message to node message came from) and is loop-free [13].

Recently, three articles [6,7,15] independently reported variations of localized routing protocols based on direction of destination. In these directional routing methods, the current node *S* uses the location information for *D* and its one hop neighbors to obtain *D*s direction, and then transmits a message *m* to several neighbors whose direction (looking from *S*) is closest to the direction of *D*. The methods differ in the choice of direction ranges. In the *compass routing* method (referred here as the DIR method) proposed by Kranakis, Singh, and Urrutia [15], the message is sent to exactly one node, having closest direction with respect to direction of destination. In the example in Figure 1, node *F* has the closest direction to line *SD* and is the selected node for forwarding the message. A counterexample showing that directional-based methods are not loop-free is given in [13].

Basagni, Chlamtac, Syrotiuk, and Woodward [6] described a distance routing effect algorithm for mobility (DREAM). It is based on the following variant of the directional method, which we call DIR algorithm. The source or any intermediate node *S* 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 *S* 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 Reference [7]. The request zone in Reference [6] is determined such that the probability of finding the destination within the zone is greater than the given threshold. DREAM algorithm [6] incorporates, in addition to the DIR method, the idea of triggering the sending of location updates (containing only the coordinates and the identifier of a node) by the moving nodes autonomously at a rate and hop distance that correspond to the node's mobility rate. For example, in Figure 2 the request zone for *S* contains nodes *A, B*, and *C*.

Ko and Vaidya [7] described independently similar R-DIR algorithm, and a few modifications of it. They observed that the request zone may not contain any neighbor of source *S* although there exists a path between the source and the destination. In the location aided routing (LAR) algorithm [7], the request zone is fixed from the source (although intermediate nodes may modify it based on more recent location information for the destination), 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. In Reference [6], the request zone is defined differently; it is determined by tangents (to the circle around the destination) from the intermediate node (not from the source). The size of the request zone depends on the average speed of the destination's movement and

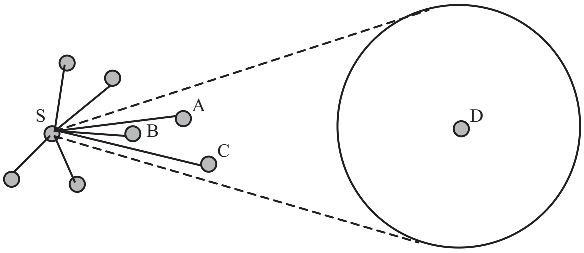

Fig. 2. The request zone for directional-based methods.

time elapsed since the last known location of the destination was recorded [6,7]. The same authors [16,17] have modified their algorithm and applied it to geocasting problem.

Geocasting protocols are surveyed in Reference [18]. We will here describe only a few that are most relevant to the contribution. An and Papavassiliou [19] describe a geocasting protocol which is basically a directional request zone method with blind flooding inside request zone being replaced by a more intelligent method. It is well known [20] that broadcasting (sending a message from one node to all the nodes inside a region) can be reliably performed (so that each node receives a copy of the packet) if only nodes from a connected dominating set retransmit the message. A dominating set consists of nodes, which 'cover' the set, that is, each node not in the set must be a neighbor of at least one node from the set. Connectivity of such sets enables propagation of information to all the nodes. An and Papavassiliou use mobility-clustering method [21] to construct one such dominating set. The mobility-clustering method is well-known clustering method by Lin and Gerla [22], where ID is replaced by mobility-based metrics, so that more stable nodes are more likely to become clusterheads. In addition, such restricted flooding (or directed guided routing [19]) in cluster structure creates a mesh, established by links between clusterheads (connected via some gateway nodes), which can be used for faster and fault tolerant geocast of subsequent traffic.

In this article we use alternate dominating set definition [23,24], which is fully localized (maintenance always remain local) while the clustering approach is quasi-local in the sense that local changes may trigger global updates of the structure. The 'generalized rule' scheme [23], is an algorithm that can be applied locally by each node, without any message exchanged with neighboring nodes, solely using the knowledge of the neighborhood. The protocol can be described as follows. First, each node checks if it has an intermediate state, which is a node that has at least two neighbors not directly connected. Then each intermediate node A constructs a subgraph G of its neighbors with higher IDs. If G is empty or disconnected then A is in dominating set. If G is connected but there exists a neighbor of A, which is not neighbor of any node from G then A is in dominating set. Otherwise A is covered and is not in dominating set. Nonintermediate nodes are never dominant. Dijkstra's shortest scheme path can be used to test the connectivity. The procedure apparently has localized maintenance. This procedure is generalized since it allows coverage by any number of neighbors. There exists a special case proposed earlier by Wu and Li [24], where the coverage was restricted to one or two neighbors only. Dominating set concept is illustrated in Figure 3.

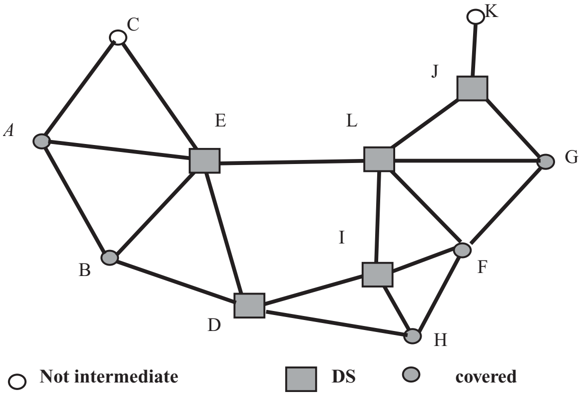

Fig. 3. Dominating set nodes E, D, I, L, J, with F covered by I and L, H covered by I.

A routing algorithm that guarantees delivery by finding a simple path between source and destination (without any flooding effect) is described in Reference [5]. The best variant of the algorithm in Reference [5] applies greedy method until current node has no neighbor closer to destination than itself. A simple distributed algorithms is described in Reference [5] for finding the planar subgraph of unit graph, and an improved version of algorithm in Reference [15], which guarantees delivery in planar graphs is applied until a closer to destination node is reached, at which point the algorithm switches back to greedy method.

Voronoi diagram of n distinct points in the plane is a partition of plane into n Voronoi regions, one associated with each point. The Voronoi region associated with node A consist of all the points in the plane which are closer to A than to any other node. It can be shown that each region is a convex polygon (possibly unbounded) determined by bisectors of A and other nodes (more precisely, each region is the intersection of all such bisectors). Okabe, Boots and Sugihara [25] gave a thorough review of concepts, applications and algorithms related to Voronoi diagrams. It is well known that the Voronoi diagram for n points in the plane can be constructed in O(n log n) time [25]. The Voronoi diagram consists of O(n) line segments. The convex hull of n nodes is the smallest convex polygon that contains given set of nodes. It can be constructed in O(n log n) time using Graham's scan algorithm [26,27].

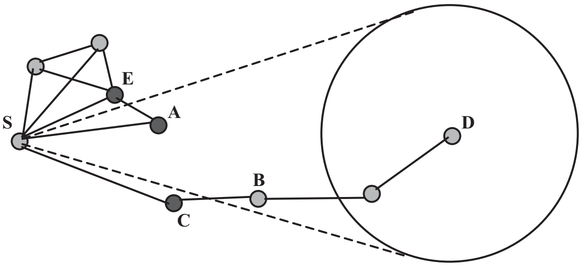

Fig. 4. The request zone modification.

3. Closest Neighbors to Destination

We shall now modify the definition of the request zone [6,7] in order to provide uniform framework with the corresponding notions in *greedy* and MFR methods. The neighbors of *S* that are located within the request zone are exactly those neighbors that are in direction closest to the direction of destination for some possible positions of destination. In other words, different position of destination within its circle lead to different choice of neighbor, and the request zone (more precisely, the corresponding angular range) may easily find such neighbors by comparing directions of all neighbors with the angular range. With this new definition in mind, we observe that the request zone defined in such way 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. Such version of directional-based scheme will be called R-DIR (range directional), and is proposed as the alternative to DIR methods used in References [6,7]. Such new definition resolves the problem of having no nodes inside the request zone [6] and may more precisely determine the expansion of the request zone if it is empty [7]. In fact, even if the zone is nonempty, the routing algorithm will be improved by possible addition of two considered nodes, if they are valid candidates to be the best choice for some possible positions of destination. For example, in Figure 4 the request zone for *S* includes, with this new definition, also nodes *E* and *C* in addition to node *A*. It appears that in some scenarios this increases the chance of delivering the message, as illustrated in Figure 4.

We shall now study the corresponding definitions of the request zone for the case of *greedy* and MFR algorithms, and propose VD-GREEDY and CH-MFR methods, in which message is forwarded to exactly those neighbors which may be closest (have most forward progress, respectively) to a possible position of *D*. These neighbors for *greedy* algorithm can be determined by using the concept of *Voronoi diagram*m for the set of nodes of network. For MFR algorithm, the corresponding concept applied is the convex hull of set of nodes.

VD-greedy geocasting method is based on determining those neighbors of current node that may be closest to a possible location of the destination. Only neighbors closer to destination than current node are considered (the reason for such choice will be explained at end of this section). In Figure 5, nodes *I, K, A, B*, and *C* are closer to *D* than *S* is, while *L* and *J* are not. Voronoi diagram of neighbors *I, K, A, B*, and *C* of *S* is marked by dashed lines. Consider one of the bisectors, for example, for nodes *B* and *C* in Figure 5. Node *S* may determine that the circle is completely on one side of the bisector, and therefore node *C* is closer than node *B* for any possible location of destination within the circle. Node *B* is therefore deleted from the forwarding list of neighbors. Forwarding nodes for *S* are therefore *A* and *C*. Note that, if bisector of each

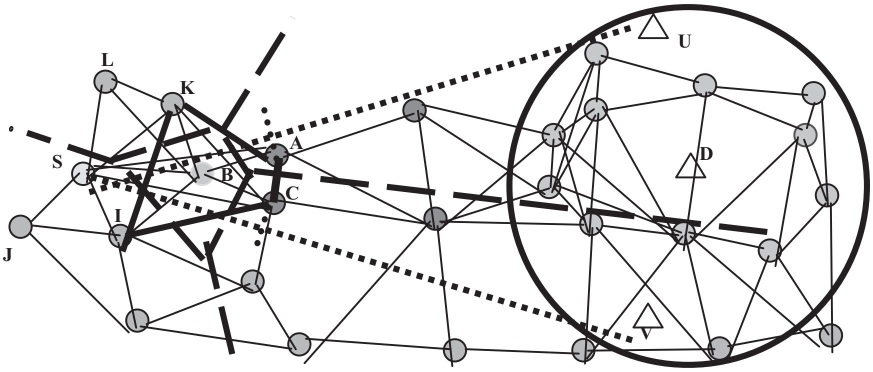

Fig. 5. The request zones for greedy and *MFR* based algorithms.

pair of nodes is similarly tested, node *S* can make a decision in O(n^2) time. This simple algorithm may be preferred if the network density is not high.

We shall also describe the corresponding selection of neighbors for the CH-MFR scheme, which is based on MFR routing algorithm [12]. Construct the convex hull CH(*S*) of all eligible neighbors of a given node *S*, and tangents from *S* to the circle of possible location of destination (see Figure 5), which touch the circle at points *U* and *V*. In Figure 5, the convex hull is CH(*S*) = *KACI* (drawn by bold lines). Find the neighbors U' and V' that will be selected by *S* if *D* is located at *U* and *V*, respectively. The message is forwarded from *S* to all neighbors that are located on CH(*S*) between U' and V' (including these two points). The forwarding neighbors for CH-MFR algorithm in Figure 5 are nodes $U' = A$, and $V' = C$. In Figure 5, the portion of H(*S*), 'cut' by orthogonals from U' and V' to the two tangents, consists of bold line *AC* and two orthogonal dotted lines to tangents.

For both VD-GREEDY and CH-MFR methods, an approximate decision can be made by selecting certain number of points on the circle boundary and finding the closest neighbor for each of them. Neither Voronoi diagrams nor bisectors are needed in this approach. However, some of the desired neighbors may not be discovered, and computation time might increase.

We shall now justify the decision to consider only neighbors closer to destination. If there is no such restriction, we will show that CH-MFR and VD-GREEDY algorithms may not remain loop-free when the past traffic is not memorized. Note first that R-DIR algorithm is based on DIR algorithm, which is not loop-free, and therefore cannot be modified itself to become loop-free in memoryless mode (unless some other concepts different from direction, e.g. distance or progress, are involved). Consider an example in Figure 6. Each of nodes *A, B*, and *C* will forward the message to two other nodes, since they are closest to nodes A', B' and C', respectively, from the circle. Thus loops can be created.

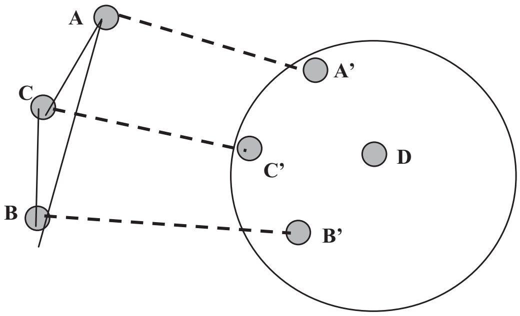

Fig. 6. Loop creation in without restricting to closer neighbors.

The restriction to closer (to destination) neighbors can be also used in CH-MFR and R-DIR algorithms. However, we propose the use, for CH-MFR, the basic MFR concept instead, that is the dot product [13]. Suppose that node *A* received the message from neighboring node *C*. *A* will consider as candidates only its neighbors *B* which satisfy $DB \cdot DA < DA \cdot DC$. The loop-free property of such CH-MFR algorithm then follows from the proof of loop-free property of MFR given in Reference [13].

The goal of proposed algorithms is to increase success rate, and decrease hop count and flooding rate. CH-MFR and VD-GREEDY are loop free, and have reduced flooding rates, since not all neighbors inside angular range will forward the routing packet. These advantages of methods proposed here over existing ones [6,7] will be confirmed experimentally in Section 5.

4. Dominating Set-Based Forwarding

We improve further all schemes by applying the dominating set concept [23], as described in literature review. Nodes in a dominating set selected by using generalized rule are connected, and their number is significantly reduced. The reduction factor depends on the graph density. Routing can be reduced to nodes in a dominating set, except possibly the first and last step, if source or destination is not in dominating set (in this case, each of them has a neighbor that is in the set, and can assists in the routing). We therefore propose here to restrict forwarding to only nodes from dominating set, which is expected to greatly reduce the flooding rate (the percentage of nodes participating in forwarding), but not to have significant negative impact on the success rate.

5. Experimental Results

We have measured the advantage of newly proposed CH-MFR and VD-GREEDY methods over newly proposed R-DIR, and the advantage of R-DIR over existing methods [6,7] by a series of experiments over several phases. Simulation was done in VC++. The phases are static (reactive) and mobile (proactive) scenarios, with and without the application of dominating sets. In the first phase, we concentrate on the

Table I. Selected neighbors count in the first hop for 200 nodes and 20% of nodes inside destination circle.

Algorithm/D	5	7	10	15	20	25	50
VD-GREEDY	1.055	1.122	1.223	1.323	1.402	1.454	1.732
CH-MFR	1.009	1.083	1.180	1.258	1.312	1.356	1.526
R-DIR	1.110	1.298	1.573	1.977	2.484	2.806	4.716
DREAM	0.601	0.720	0.976	1.358	1.838	2.202	4.103
LAR1	1.338	1.700	2.319	3.383	4.442	5.274	9.855
LAR2	1.590	2.088	2.905	4.275	5.681	6.889	13.217

performance of geocasting protocol. Assuming that the speed of message broadcast is significantly larger than the speed of node movement, we observed that experiments on static nodes have already shown reliable comparison data in case of geocasting protocol. They also served as proof of concept for the case of routing, and in fact were giving reliable data for the route discovery phase, for the search outside the region. We performed experiments for geocasting where the region itself was not mobile, but nodes were moving. However, the comparative data did not differ, and we decided to show only data for static case.

The static network phase was subdivided into one hop and multihop measurements. In the one-hop case, only the first hop is considered. For given number of nodes n and average degree k, we are taking the percentage p of nodes from the network as the size of circle around destination. The average number of selected neighbors for retransmission is measured, when the source is outside of circle containing the destination. Table I presents the average data about the number of selected neighbors for random unit graphs with 200 nodes and degrees 5, 7, 10, 15, 20, 25, and 50, when circle containing destination has $p = 20\%$ of all nodes. These data serve to explain results obtained in other phases. Only connected pairs of source and destination were considered. Dominating set restriction was not applied.

In the multihop measurements step, the nodes are still static, but the routing process continues beyond the first hop. The selected neighbors are marked, and the routing continues from these nodes as discussed. When the message reaches a node inside the circle, the shortest path algorithm is used to verify the connectivity and complete routing. At each node, only neighbors closer to destination are considered, if any. Success rates, hop counts of shortest path, and flooding rates (percentage of marked nodes) are measured. Tables II and III show percentages of successful

Table II. Percentage of successful deliveries for 200 nodes and $p = 20\%$ of nodes inside circle.

Algorithm/K	5	7	10	15	20	25	50
VD-GREEDY	82.10	93.10	98.50	99.95	100.00	100.00	100.00
CH-MFR	74.40	89.35	98.00	99.85	100.00	100.00	100.00
R-DIR	67.85	85.65	97.15	99.70	100.00	99.95	100.00
DREAM	23.05	35.60	52.00	77.10	89.85	94.40	99.45
LAR1	69.30	82.05	93.15	98.70	99.75	99.80	100.00
LAR2	55.65	83.85	97.15	99.70	100.00	99.95	100.00

Table III. Percentage of marked nodes.

Algorithm/K	5	7	10	15	20	25	50
VD-GREEDY	8.32	10.85	12.03	11.15	10.08	9.30	6.37
CH-MFR	6.43	8.90	10.74	10.55	9.71	8.99	6.14
R-DIR	6.26	9.57	12.64	14.30	14.83	15.48	18.56
DREAM	1.29	1.94	3.26	5.25	7.16	8.56	13.93
LAR1	12.02	19.19	25.29	29.54	30.98	32.74	36.23
LAR2	9.29	16.16	26.67	37.93	45.21	51.21	65.46
SP	4.56	3.25	2.40	1.82	1.52	1.35	0.95

Table IV. Average hop counts for the shortest route.

Algorithm/K	5	7	10	15	20	25	50
VD-GREEDY	12.29	9.63	7.65	5.98	5.12	4.59	3.41
CH-MFR	12.03	9.50	7.64	5.98	5.12	4.59	3.41
R-DIR	11.76	9.53	7.68	6.02	5.14	4.61	3.41
DREAM	9.61	8.13	6.85	5.78	5.09	4.60	3.41
LAR1	12.02	9.49	7.61	5.99	5.12	4.59	3.40
LAR2	10.32	9.25	7.63	5.97	5.11	4.59	3.40
SP	13.03	9.88	7.67	5.98	5.11	4.59	3.40

deliveries and marked nodes for 200 nodes and $p = 20\%$, showing superiority of VD-GREEDY and CH-MFR and advantage of R-DIR over DREAM and *LAR*. Source is restricted to be far enough not to reach directly any point from destination circle, and only connected source-destination pairs are considered. Marked nodes having neighbor(s) inside destination circle do not forward message further, but hop count measure considers all intermediate nodes from source up to destination. SP in several tables refers to the shortest path routing scheme.

Table IV shows average hop counts for shortest among found successful routes (route is successful if the last marked node on it can reach a node inside destination circle). The data in tables II–IV clearly indicate that R-DIR is superior to DREAM and LAR, but is inferior to CH-MFR and VD-GREEDY. At low degrees DREAM and LAR fail frequently, while at higher degrees they flood the network considerably to achieve high success rate.

Tables V, VI, and VII show significant reduction in percentage of marked node after applying dominating sets with marginal impact on percentage of successful deliveries and hop counts for VD-GREEDY, CH-MFR, R-DIR, and LAR2. However, success rate is significantly reduced in LAR1 and DREAM.

The experiments with moving nodes were designed to evaluate proactive routing performance. We place $n = 200$ nodes in an area of length $L = 640$ units and width $W = 480$ units. Transmission range R was determined so that the expected number of neighbors is $k = 5$, 6, 7, 8, 9, 10, 11, and 15, using relation $k = (n-1)R^2\pi/(\mathrm{LW})$. Random walk model was used. Each node is moving at a speed of x units per clock tick in a random direction, where x is randomly selected number for each node in interval [0,2], and

Table V. Percentage of successful deliveries after applying dominating sets for 200 nodes and $p = 20\%$ of nodes inside circle.

Algorithm/K	5	7	10	15	20	25	50
VD-GREEDY	77.90	94.40	99.35	99.85	100.00	99.90	100.00
CH-MFR	65.90	86.95	97.20	99.05	99.70	99.05	99.75
R-DIR	57.30	82.80	95.10	97.65	98.95	98.35	99.00
DREAM	15.65	22.80	30.60	40.10	44.30	48.80	72.75
LAR1	59.10	74.65	86.95	92.70	93.80	93.25	95.50
LAR2	49.55	78.05	93.45	97.75	98.75	98.20	99.40

Table VI. Average hop counts for the shortest route after applying dominating sets.

Algorithm/K	5	7	10	15	20	25	50
VD-GREEDY	11.52	9.75	8.09	6.48	5.66	5.13	3.68
CH-MFR	10.81	9.53	8.04	6.47	5.66	5.11	3.68
R-DIR	10.45	9.48	8.06	6.48	5.69	5.14	3.68
DREAM	7.96	7.34	6.50	5.58	5.03	4.58	3.52
LAR1	10.89	9.42	7.96	6.46	5.66	5.08	3.65
LAR2	10.19	9.37	8.00	6.45	5.65	5.10	3.67
SP	13.23	10.13	8.09	6.48	5.65	5.12	3.68

Table VII. Percentage of marked nodes after applying dominating sets.

Algorithm/K	5	7	10	15	20	25	50
VD-GREEDY	6.61	8.33	8.51	6.88	5.81	5.13	3.44
CH-MFR	4.87	6.45	7.07	6.10	5.08	4.59	3.15
R-DIR	4.17	6.00	6.95	6.38	5.68	5.51	4.83
DREAM	0.67	0.82	1.08	1.28	1.43	1.66	2.33
LAR1	6.28	9.23	10.50	9.81	8.60	8.48	7.45
LAR2	4.72	7.33	9.50	9.71	9.18	9.61	9.43
SP	4.64	3.38	2.62	2.08	1.80	1.63	1.11

Table VIII. Percentage of successful deliveries for 200 mobile nodes, without dominating sets.

Algorithm/K	5	6	7	8	9	10	11	15
VD-GREEDY	28.48	44.71	62.71	73.94	85.13	90.27	90.84	94.82
CH-MFR	24.58	39.46	56.68	69.58	82.20	87.90	89.29	94.55
R-DIR	28.73	46.97	65.37	77.22	87.51	92.02	92.40	95.23
DREAM	1.08	1.49	2.12	2.91	3.86	5.19	5.98	11.24
LAR1-P	17.37	29.79	41.95	53.01	63.38	70.13	72.16	83.34
LAR2-P	31.32	55.08	74.47	85.97	93.81	97.17	97.75	99.46

random direction is independently selected for each time clock. Each node is reflected from the ‘wall’ if it hits the wall, sends a Hello message to its one hop neighbors every 10 clock units, and floods the network with its position every 70 clock units. Since network may be partitioned, flooding may not reach all nodes. The size of destination circle was determined based on the speed and the time difference from the last known position, independently at each node. Since LAR1 and LAR2 are here applied in described proactive setting (instead of originally described reactive one), the names used here are different: LAR1-P and LAR2-P. All methods will therefore have the same control overhead, and the performance measures from the second phase will be considered. Two sets of experiments are performed, one without applying dominating sets, and one after applying dominating sets concept. The obtained results are given in Tables VIII–XIII.

The data in Tables VIII–X show that VD-GREEDY, CH-MFR, and R-DIR perform better than DREAM,

Table IX. Average hop counts for the shortest route, without dominating sets.

Algorithm/K	5	6	7	8	9	10	11	15
VD-GREEDY	9.57	9.89	9.27	8.60	8.00	7.54	7.14	5.91
CH-MFR	9.15	9.52	8.99	8.46	7.93	7.49	7.12	5.92
R-DIR	9.68	10.09	9.52	8.85	8.24	7.76	7.39	6.13
DREAM	5.85	6.74	6.01	5.57	5.42	5.32	5.18	4.88
LAR1-P	9.51	9.91	9.22	8.48	7.92	7.47	7.09	5.90
LAR2-P	9.52	10.03	9.39	8.64	7.97	7.48	7.08	5.86

Table X. Percentage of marked nodes, without dominating sets.

Algorithm/K	5	6	7	8	9	10	11	15
VD-GREEDY	2.91	4.37	5.32	5.63	5.89	5.94	5.74	5.11
CH-MFR	2.38	3.63	4.55	5.03	5.43	5.54	5.43	4.98
R-DIR	3.78	6.43	8.51	9.86	11.05	11.53	11.44	10.99
DREAM	0.12	0.16	0.21	0.26	0.32	0.40	0.45	0.80
LAR1-P	4.77	8.60	11.40	13.18	14.96	16.25	16.91	18.57
LAR2-P	8.31	16.83	23.80	30.04	36.26	40.97	44.14	55.33

Table XI. Percentage of successful deliveries for 200 mobile nodes, with dominating sets.

Algorithm/K	5	6	7	8	9	10	11	15
VD-GREEDY	32.00	49.92	68.09	77.18	86.70	91.12	91.53	93.51
CH-MFR	26.89	42.23	59.21	70.34	81.57	86.39	87.79	91.41
R-DIR	29.83	47.75	65.20	76.78	85.87	90.27	91.01	93.40
DREAM	0.80	0.84	1.08	1.41	1.72	1.99	2.24	3.37
LAR1-P	14.55	24.10	33.96	42.29	50.09	55.09	55.79	62.44
LAR2-P	27.85	48.74	66.84	79.42	88.36	92.90	94.26	97.34

Table XII. Average hop counts for the shortest route after applying dominating sets.

Algorithm/K	5	6	7	8	9	10	11	15
VD-GREEDY	9.84	10.16	9.63	8.94	8.38	7.96	7.60	6.41
CH-MFR	9.34	9.68	9.27	8.71	8.26	7.86	7.52	6.37
R-DIR	9.61	10.00	9.51	8.90	8.36	7.94	7.59	6.44
DREAM	5.14	5.23	5.39	4.97	4.79	4.66	4.62	4.33
LAR1-P	9.35	9.91	9.40	8.69	8.25	7.79	7.46	6.32
LAR2-P	9.45	9.96	9.46	8.83	8.26	7.83	7.47	6.33

Table XIII. Percentage of marked nodes after applying dominating sets.

Algorithm/K	5	6	7	8	9	10	11	15
VD-GREEDY	2.68	4.03	4.71	4.84	4.93	4.90	4.65	3.91
CH-MFR	2.17	3.29	3.99	4.24	4.45	4.45	4.28	3.72
R-DIR	2.94	4.91	6.21	6.99	7.56	7.74	7.48	6.66
DREAM	0.06	0.08	0.09	0.10	0.12	0.13	0.14	0.19
LAR1-P	2.25	3.99	5.04	5.69	6.22	6.46	6.36	6.10
LAR2-P	4.13	7.77	10.21	12.02	13.46	14.25	14.39	14.57

LAR1-P, and LAR2-P. VD-GREEDY, CH-MFR, R-DIR, and LAR2-P have almost same success rate, but, LAR2-P has a very high flooding ratio to maintain the same success rate.

The data in Tables XI–XIII show results of the above algorithms after applying dominating set. The results show that dominating sets are very effective in reducing the flooding ratio in a dense network without affecting the success rate and hop counts especially for VD-GREEDY, CH-MFR, and R-DIR. The flooding ratio for higher densities is reduced even more dramatically [23,24], but we limited degree to 15 because of otherwise extremely high communication overhead. However, success rate for DREAM, and LAR1-P is significantly reduced after applying dominating sets.

6. Conclusions

Our theoretical and experimental analysis of new CH-MFR and VD-GREEDY schemes, with and without dominating set enhancement, have clearly indicated their significant overall advantage in terms of loop avoidance, success rates, and flooding rates. The improvement was concentrated on the performance outside the geocasting region, or region-containing destination in case of routing. Inside the region, we assumed the application of either blind flooding, or intelligent flooding, or a position-based routing toward exact position of destination. This part was assumed same for all methods and was not discussed here. This, however, does not mean that this is the best approach that one could take. Our research continues toward finding even better solutions. While in this article the emphasis was on loop freedom and reduced flooding without impacting success rate, the further research is directed toward novel algorithm inside the region, and modified geocasting algorithm to match it. We observed already [1] that one can use path and position-based GFG routing protocol with guaranteed delivery [5] to reach the region with minimized flooding. However, the region itself does not need to be connected, therefore the node that is reached may be disconnected from the destination, or disconnected from a significant number of nodes in geocast region. We are developing a novel algorithm that addresses this problem, and in fact incorporates GFG and multi-path-based approach proposed and described here into a single and hopefully optimal geocast protocol. The details of it are nontrivial, and will be described in our future research [28].

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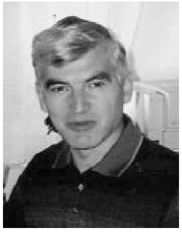
Authors' biographies



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