

GCRP: Geographic Virtual Circuit Routing Protocol for Ad Hoc Networks

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Abstract

Geographic routing exploits localized information concerning explicit node locations to make forwarding decisions. This approach adapts well to the dynamic nature of ad hoc networks. However, it is subject to increased overhead during the local minimum recovery process. In this paper we specify GCRP, a routing protocol based on the novel geocircuit paradigm, that exploits already discovered paths to avoid repeated recoveries from the same local minimums. The proposed protocol is established to exhibit loop-freedom, while robustly eliminating mobility-induced loops. Performance analysis demonstrates significant advantage of GCRP relative to conventional geogram routing, over a wide range of network environment conditions. Gains increase as limiting network parameters are increased, namely node mobility, traffic load, network size and density. Effective repair of broken geocircuits preserves scalability in highly mobile environments.

1. Introduction

Ad hoc networks have been the object of increased research interest during recent years. Their dynamic nature enables rapid deployment as well as increased flexibility and cost effectiveness. However, it imposes challenges in the provision of important network services, including that of routing. Geographic routing is a localized approach exploiting geographic information. Nodes make forwarding decisions based upon local topology information, concerning explicit node locations. Although it does not guarantee path optimality due to its localized nature, geographic routing achieves to find routes with little overhead. Since obtaining optimal routes, at least deterministically, is an open problem in ad hoc networks, finding correct routes quickly and at low cost makes geographic routing a very promising approach.

However, due to the distributed nature of geographic

routing, local optimums may be reached, wherein a node is 'optimal' with respect to its local view of the network. They are known as *local minimums*. Techniques adopted to recover from these impose an overhead in the overall routing algorithm, jeopardizing the initial benefit of utilizing localized information.

Geocircuits [7, 8] cache routing information to avoid repeated recovery from the same local minimums. The term depicts the integration of virtual circuits in geographic routing, which is novel in this paradigm. Maintaining state information is however susceptible to routing packets endlessly in loops. Hence specific effort needs to be directed towards timely eliminating loops from routing tables. Furthermore, we expect geocircuits to break, especially in highly mobile networks. The aim of this paper is to specify a loop-free routing protocol employing geocircuits, establish its correctness, and validate its performance through analysis based on thorough simulations. It is also our objective to propose a low cost geocircuit repair technique. Advances are introduced in the local minimum recovery scheme and mobility model. GCRP is compared to conventional geographic routing, where packets are routed independently, as *geograms*.

In GCRP, geocircuits are established during data packet forwarding. Geographic forwarding decisions are based on a distance minimization criterion. Depth first search is utilized to recover from local minimums, wherein no neighbor is known to be closer to the destination. Upon recovery, geographic forwarding is resumed to further minimize cost. Routing information is cached and utilized by succeeding packets. Broken geocircuits are repaired timely, at low cost. Protocol loop-freedom and correctness are established.

The rest of this paper is organized as follows. Section 2 presents the two routing strategies in more detail. The proposed routing protocol and proof of its correctness are presented in Section 3. In Section 4, we describe our simulation environment, model, and experimental design. The simulation model is designed in order to allow for a fair validation of GCRP in comparison to conventional geographic

routing. Simulation results are presented and analyzed in Section 5. We conclude this paper in Section 6.

2 Geograms versus Geocircuits

Geographic routing belongs in the class of location-based routing schemes [14]. These schemes employ location information to reduce the overhead of routing.

2.1 Geograms

Geographic routing exploits localized geographical information to forward packets directly, without any prior route search, to exactly one neighbor. This is named *geogram* routing, to stress that packets are forwarded independently like datagrams. The restricted information maintained at each station concerns explicit location of stations in the vicinity. Typically, each station maintains the geographical positions of its one-hop neighbors.

Geographic Forwarding: Upon originating a packet, a source may obtain location information of the destination, utilizing an underlying mobility management scheme, in a manner described in the sequel. This information is recorded on the packet header. Each intermediate node (including the source node) selects the next hop based solely on the destination node's location and the local view of the network it maintains. A metric is employed to evaluate available forwarding choices and optimize the decision according to the available information. The most commonly employed criteria are direction minimization [13], distance minimization, and forward progress maximization.

Local Minimum Recovery: Since individual forwarding decisions are based on local information, they may only be locally optimized. Geographic routing schemes may not guarantee globally optimal paths. The best (possibly also the only) route to a destination may require temporary movement against the utilized forwarding criterion. *Local minimums* may be encountered, where the current node is better than all potential next hop choices, according to the employed criterion. Assume that a packet that was originated at node S and destined to node D encounters a local minimum at node N , known as concave node. Then the intersection of the transmission range of N with the area of better (according to the utilized criterion) potential neighbor locations, known as void, is empty of nodes. Figure 1 illustrates a void when the forwarding criterion is minimization of Euclidean distance to the destination. It is the intersection of the transmission range of N with the circle of center D and radius equal to their distance DN .

A mechanism to recover from local minimums may be employed. This may be flooding, depth-first search [17, 10], breadth-first search, or the right hand rule [13, 4, 11] for

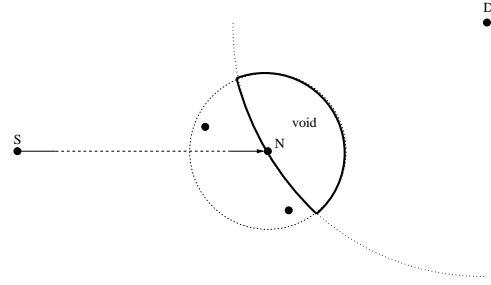


Figure 1. Local Minimum

traversing faces of a planar sub-graph of the graph representing the network. A termination condition is typically employed to adopt a tradeoff between the overhead of recovering from the local minimum and the probability of finding an existing route. In [4, 11], geographic forwarding is resumed when a node better (in this case closer to the destination) than the concave node is reached.

Mobility Management: Mobility management involves the mechanisms responsible for maintaining node locations and supporting queries and updates. An underlying location sensing scheme, like GPS, is typically assumed in geographic routing.

2.2 Geocircuits

As *geocircuit* we denote a virtual circuit in geographic routing. To each geocircuit correspond *GC-numbers*, one for each link along the path. Each node maintains a table that holds an entry for each established geocircuit traversing it, named the *GC-number translation table* (GC-table). Each entry in the table maps an inbound interface number to an outbound interface number, for a specific geocircuit.

The first packet issued for some destination employs geogram routing and establishes a geocircuit as it is routed. Consecutive packets are routed according to GC-number mappings. The GC-number corresponding to the link along which a packet is forwarded is recorded on the packet's header, on the *GC-number field*.

2.3 Comparison

Geocircuit routing is proposed to detour re-implementation of the expensive local minimum recovery procedure. However, geogram routing is expected to achieve locally optimal forwarding decisions for each individual packet, exploiting the localized information available at each intermediate node. Note that locally optimal forwarding decisions do not guarantee a globally optimal path.

In highly mobile ad hoc environments, we anticipate that geocircuits may break. Furthermore, GC-tables require additional storage resources, that need to be evaluated. Finally, if these contain a loop, packets will be circulating endlessly, consuming valuable bandwidth and fail to be delivered. This will persist for the lifetime of the geocircuit, in contrast to the geogram approach, wherein forwarding decisions independently exploit up-to-date information.

3 Geocircuit Routing Protocol

Upon originating a packet for a new destination, a node employs the underlying mobility management scheme to obtain the destination’s location. A total of three queries are employed with increasing waiting time intervals if no reply is received from the location database. If the destination location is resolved, the session begins originating packets. Each source node caches the coordinates of its last destination, in order to avoid querying for each packet during a session.

3.1 Geographic Forwarding

Nodes maintain *neighbor tables*, recording the positions of their one-hop neighbors. Each node communicates this information by broadcasting a hello message bearing its identifier and position according to a Poisson process of rate λ_H . This information is also piggybacked whenever a data packet is forwarded. A neighbor table entry also includes a time stamp, recording the time when the information was obtained. A predefined parameter l_N determines the lifetime of the entries. If a node does not hear from a neighbor for this time interval, it assumes that the corresponding link is broken and deletes the entry. The forwarding decision criterion is Euclidean distance minimization. Packets establish and are forwarded along geocircuits, as described in the previous section.

3.2 Local Minimum Recovery

We propose a combination of depth-first search and geographic forwarding resumption for local minimum recovery. A bounded depth-first search is employed, forwarding data packets directly. The neighboring nodes are ordered in ascending distance from the destination, and are visited in this order. No node is visited more than once. A node may know if it has previously seen a packet by recording the packet’s identifier. In order to reduce the overhead of the local minimum recovery and avoid searching for a non-existent path, a predefined parameter D_{MAX} determines the maximum depth of the search. In addition to this, we switch back to geographic forwarding when a node that lies closer to the destination than the concave node is reached. For this

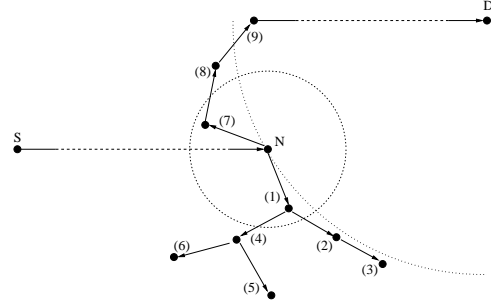


Figure 2. Local Minimum Recovery

reason, the concave node records its geographical position (or distance to destination) on the data packet. Such a local minimum recovery is depicted in Figure 2, where a maximum depth $D_{MAX} = 3$ hops is assumed. The numbers in brackets illustrate the order in which nodes are visited during the depth-first search. The local minimum is recovered at the ninth node, which is closer to the destination D than the concave node N . The packet is switched back to geographic forwarding mode.

When the local minimum is resolved, a control packet is issued addressed as the *GC-setup packet*. It follows the inverse of the sub-path that is derived during the local minimum recovery, setting up the virtual circuit. It conveys the nodes it has to traverse. For this reason, we introduce an addition in depth-first search: a data packet always maintains the current path to the root of the search tree. When it searches in depth it appends nodes, whereas when it back traces it deletes them. Note that the length of this path is bounded by the maximal depth D_{MAX} , and hence the memory requirement is $O(1)$.

3.3 Geocircuit Repair

To account for the dynamic nature of ad hoc networks, GC-table entries that are no longer in use are removed. A predefined lifetime l_{GC} determines whether a recorded entry may be considered reliable or stale. Entries that haven’t been utilized for as long as l_{GC} are erased, to preserve memory space. Assume a geocircuit connecting nodes S and D (Figure 3(a)), traversing the link AB . The GC-table entries at nodes A and B are shown in Figure 4. GC-number j corresponds to the link AB . The GC-number of the upstream link is mapped to j in the GC-table of node A . GC-number j is then mapped to the number of the next link towards D , in the GC-table of B . The time stamps associated with each geocircuit entry, T_i and T_j respectively, are reset whenever the entries are utilized.

Due to the dynamic topology of ad hoc networks, the lifetime of a geocircuit is bounded and unpredictable. An

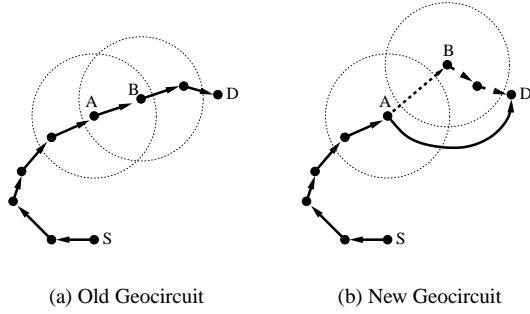


Figure 3. Geocircuit Repair

...
GC-number i	GC-number j	T _i
...

...
GC-number j	GC-number k	T _j
...

Figure 4. GC-Number Translation Table Entries

approach to rebuild a broken geocircuit is proposed to anticipate for such an event. The packet that realizes that its subsequent node in the circuit is no longer a neighbor employs geogram routing and at the same time rebuilds the broken part of the geocircuit. In Figure 3(b), node *A* encounters a disconnection with node *B* and repairs the downstream part of the geocircuit towards the destination *D*. The geocircuit is rebuilt at no larger cost than initial geocircuit establishment. Entries in the disconnected part of the old circuit are soon deleted, since they are no longer utilized.

3.4 Proof of Correctness

Loop-freedom will be established first. Loops may form during convergence time, when stale information is still available. In GCRP, loops may also form if distinct sub-paths of specific forwarding mode along the same geocircuit intersect. Finally, they may result from node mobility.

A technique is devised in order to prevent loop-formation in the GC-tables distributed in the network. An identifier uniquely determining a geocircuit, the *GC-identifier*, is appended to each GC-table entry. This identifier may be formed by the concatenation of the identifier of the source node and a sequence number. Before recording a new mapping, a node searches its GC-table for a potential existing entry corresponding to the same geocircuit. If one is found, its outgoing GC-number is replaced by the GC-number derived by the new forwarding decision. We will establish that the above is sufficient to assure loop-freedom. We know that the distinct sub-paths obtained during geographic forwarding

or local minimum recovery addressed individually are loop free [16]. We denote the *i*-th forwarding mode interval as I_i and the sub-path that is derived during I_i as P_i .

Lemma 1 Consider a static wireless network. Nodes in subsequent sub-paths obtained during geographic forwarding mode are better (with respect to the distance minimization criterion) than those in preceding sub-paths obtained in the same mode.

Proof: Assume two random sub-paths P_i and P_{i+2j} obtained during geographic forwarding modes, where $j > 0$. Note that since geographic and local minimum recovery forwarding modes are alternating, the index distance of these sub-paths is even ($2j$). Sub-paths P_i and P_{i+2j} are separated by j sub-paths that resulted from a successful local minimum recovery and $j - 1$ sub-paths that resulted during geographic forwarding mode. Since the local minimums were surmounted, the last node on each intervening local minimum recovery sub-path is better (ie. closer to the destination) than the first one (from GCRP specification). This also holds for intervening sub-paths obtained during geographic forwarding, since forwarding decisions always lead to better nodes. Hence, the first node on each geographic forwarding sub-path P_{i+2j} is better than the last node on any preceding sub-path P_i obtained in the same manner. Since the nodes of any such sub-path are of strictly decreasing distance to the final destination, it follows that the nodes on P_{i+2j} are closer to the destination than the nodes on P_i . We have therefore established the Lemma. \square

Lemma 2 Consider a static wireless network. Geographic forwarding mode in GCRP will not intersect with any upstream node in the path.

Proof: Let P_i be a random sub-path obtained during geographic forwarding mode. It suffices to establish that no node of the upstream path can be as close to the destination as the nodes in P_i . This follows from Lemma 1 for upstream nodes obtained during geographic forwarding. If an upstream node obtained from a local minimum recovery was as close as a node in P_i , the protocol would have switched to geographic forwarding. We have therefore established that P_i cannot intersect with the upstream part of the path. \square

Theorem 1 Consider a static wireless network. GC-number translation tables of GCRP are loop-free.

Proof: It follows from Lemma 2 that loops may only form during local minimum recovery. It therefore suffices to prove that all loops formed in this manner are eliminated at their creation. Assume that the sub-path P_i derived during local minimum interval I_i intersects the upstream part

of the path at least once. Note here that it cannot intersect itself, as nodes involved in depth-first search do not forward the same packet more than once. Assume N is the last node of intersection. This is the first one reached by the GC-setup packet traversing the inverse of P_i to set up the geocircuit. The old entry concerning the geocircuit will be overwritten so that the path in between the two traversals of node N is omitted. This will detour all possible intervening intersections, eliminating all loops. Hence any loop traversed by the packet setting up the geocircuit will be excluded from the routing tables. We have therefore established that GCRP is loop-free in a static environment. \square

Theorem 2 *GC-number translation tables of GCRP preserve loop-freedom property in a mobile wireless network.*

Proof: Loops that are formed during the same local minimum recovery interval are eliminated as the GC-setup packet traverses the inverse of the sub-path. This is established similarly to the proof of Theorem 1. It is also straightforward to observe that loops resulting during geographic forwarding are eliminated as they are formed. As a result, the GC-tables are always loop-free. \square

Theorem 3 *Consider a static wireless network. GCRP terminates in finite steps, while packets are either delivered or dropped.*

Proof: We infer from Lemma 2 and Theorem 1 that packets may only traverse a loop during local minimum recovery, while in geocircuit establishment or repair. A loop may not persist (it will only be traversed once), since no node is visited more than once, while the packet is dropped in case of failure to recover from the local minimum. Furthermore, the total number of nodes visited during a local minimum recovery process is finite, since a packet may only reach D_{MAX} hops away from the concave node. The total hops in geographic forwarding is also finite, since distance to destination is descending. The same holds for the number of alternations between the two forwarding modes. We observe that if routing along a geocircuit fails, geogram routing is resumed, while if geographic forwarding fails, local minimum recovery is activated. If the depth first search fails to find a location closer to the destination than the concave node, the packet is dropped. As a result, GCRP terminates in finite hops, while packets are either delivered to their destination or dropped. \square

In a mobile network, a packet may reach the advertised location of the destination node, which may have moved away. In such a case, the packet is broadcasted once before it is dropped. Furthermore, packets may get in mobility-induced loops, even though these are not recorded on the GC-tables (Theorem 2). To assure correctness in such an event, a predefined parameter l_P limits the maximum hops a packet may traverse.

4 Simulation Model

The main objective of the simulation model developed is to enable an unbiased, systematic analysis of the performance of GCRP. We chose the CSIM simulation engine [1], to maximize flexibility in our model.

4.1 Mobility Model

We introduce correlation between the movement of a node in successive time intervals, as well as between the mean and variance of node velocity, in the entity mobility model in [15]. A Poisson stochastic process of rate λ_M partitions time in epochs. During each epoch, a velocity vector characterizes the movement of a node. The velocity value of consecutive epochs is an independent identically distributed random process, following a normal distribution of mean $\bar{v} = v_{MAX}/2$ and standard deviation σ_{vel}^2 . Values falling out of the $[0, v_{MAX}]$ range are bounced back until they fall within the range. Velocity directions of consecutive epochs are dependent, following a Markov stochastic process. Specifically, the direction of movement is normally distributed with mean its value in the previous epoch and standard deviation σ_{DIR}^2 . The direction of each initial epoch is selected uniformly within $[0, 2\pi]$. Nodes hitting area boundaries bounce back in. The correlation among the velocity absolute value and standard deviation is presented in the experimental design section.

4.2 Traffic Model

Traffic sessions originate according to a Poisson process of rate λ_S , while the duration of each session is an exponential random variable of mean μ_S . The source and destination nodes of each session are uniformly selected. Packets have a uniform length L and arrive with a constant bit rate b_P within each session.

4.3 Mobility Management

We assume that each node may obtain its current geographical position by an underlying localization scheme, like GPS or some equivalent. Analysis of location management is beyond the scope of this paper. However, we implement a simplified scheme, in order to account for it within the scope of geographic routing. The network deployment area is partitioned in equally sized regions of edge G . Each region has a fixed component in its center that serves as a location server for a number of network nodes (*home region*). The network nodes are evenly distributed among the regions, according to a deterministic many-to-one mapping. Each location server is equipped with a transceiver of the same power with the ones borne by mobile network nodes.

Table 1. System Parameters.

C	11 Mbits/sec
L	512 Bytes
d_{proc}	0 sec
s	infinite
R	250 m
G	800 m
μ_S	30 sec
b_P	16 Kbps
λ_M	0.0333 epochs/sec
σ_{DIR}^2	$\pi/4$ rad
λ_H	3.8387 message/sec
D_{MAX}	3 hops
l_N	12.0982 sec
l_{GC}	12.0982 sec

Location updates, queries and replies employ geogram routing. A node initiates an update in a static manner, whenever it enters a different region.

4.4 Experimental Design

A graphical technique is employed to determine the transient period of our system. Statistical independence of 10 observations is ensured by the method of batch means. 95% confidence intervals are utilized to indicate statistical significance of output mean estimations.

System parameters (Table 1) were selected so as to provide a realistic, unbiased model. We denote the transmission rate as C , the processing delay as d_{proc} and the propagation speed as s . We select the hello rate λ_H and the neighbor and GC-table lifetime l_N and l_{GC} by experimentally estimating the rate of change in the one-hop neighborhood of nodes, and the packet rate b_P to model compressed voice.

We choose the network deployment area E to be a dependent parameter, in order to preserve a constant network density d while varying the number N of nodes and a constant number N of nodes while varying network density d . We define density as the mean number of nodes within a πR^2 area. The total number of nodes N in the network are therefore $dE^2/(\pi R^2)$. Solving for E , we obtain Equation 1. We select the velocity standard deviation σ_{vel}^2 as a linear function of the maximum velocity v_{MAX} (Equation 2), so that the velocity is with probability 1/2 within the range $[\bar{v} - v_{MAX}/8, \bar{v} + v_{MAX}/8]$.

$$E = R \cdot \sqrt{\pi N/d} \quad (1)$$

$$\sigma_{vel}^2 = v_{MAX}/8 \quad (2)$$

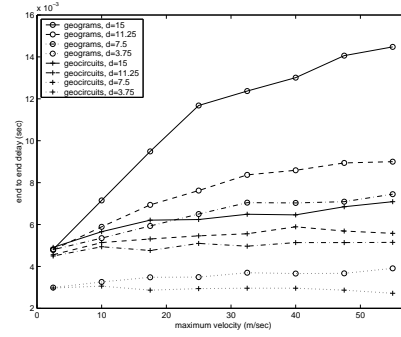


Figure 5. End-to-End Delay vs. Network Mobility and Density.

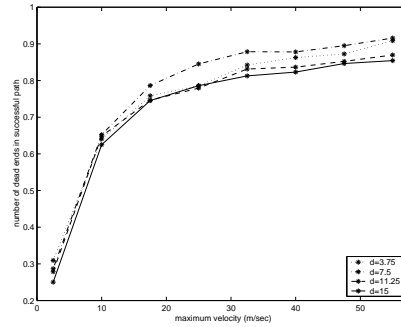


Figure 6. Number of dead ends in successful path vs. Network Mobility and Density.

5 Simulation Results and Analysis

In order to analyze the performance of GCRP, we vary the maximum velocity v_{MAX} , total number of nodes N , the network density d , and traffic session rate λ_S . When not varied, these parameters are set to $v_{MAX} = 40$ m/sec, $N = 100$ nodes, $d = 7.5$, and $\lambda_S = 0.0150$ sessions/sec, representing an average network environment. Performance is compared to geogram routing, employing design choices equivalent to geogram routing in geocircuit setup in GCRP.

5.1 GCRP Protocol Performance

We observe that GCRP exhibits a lower delay, and this advantage increases as node mobility increases (Figure 5). This contradicts our intuition that the performance of GCRP would degrade in highly mobile environments, due to geocircuit breakages. It is however evident that geocircuits are robust enough even at maximal velocities of $v_{MAX} = 55$

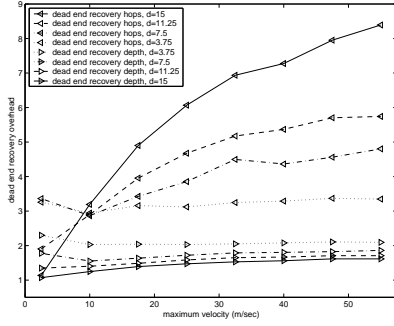


Figure 7. Local Minimum Recovery Overhead vs. Network Mobility and Density.

m/sec. The probability of encountering a void during a routing path increases as mobility increases (Figure 6). Moreover, the advantage gained by detouring local minimum recovery increases. This is visualized as the difference between the average total number of hops traversed versus the average depth of the depth-first search (Figure 7). It is also illustrated in Figure 8, wherein a session issued from node S to D encounters a dead end at node N . In geogram routing, all packets traverse all the illustrated links to recover from the dead end. In GCRP, after the geocircuit is established, packets only traverse the links in bold arrows. The scalable performance of GCRP as mobility increases stems from the combined effect of the increased susceptibility to local minimums and the increased overhead of local minimum recovery.

The probability that paths encounter local minimums and the advantage of local minimum recovery also affect the routing protocol performance as a function of density (Figure 5). We observe that GCRP exhibits lower delay than conventional geogram routing, while the advantage becomes more evident as density increases. This contradicts our intuition that increased density would render the negative effect of local minimums on geographic routing negligible, hence permitting no advantage margin for GCRP. We observe that the probability that paths encounter dead ends does not vary much with density (Figure 6). As density increases, the susceptibility of individual hops to local minimums decreases. However, density is inversely proportional to the network area (Equation 1). Network area is proportional to the average path length in geographic routing. Indeed, the network diameter DM may be approximated as the network area diagonal divided by the transmission range (Equation 3). As a result, the susceptibility of total routes to dead ends is comparable as density varies. The total number of hops for local minimum recovery in-

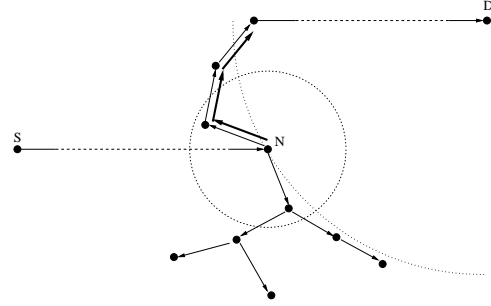


Figure 8. Local Minimum Recovery Overhead

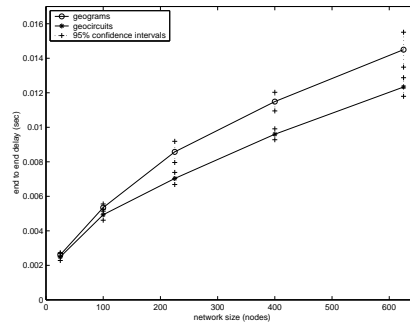


Figure 9. Average End-to-End Delay vs. Network Size.

creases a lot as density increases, while the average depth decreases (Figure 7). The number of nodes within maximal depth of D_{MAX} is larger in denser networks, hence there are more nodes to be examined by depth first search. Moreover, the maximal depth D_{MAX} may often be exhausted in a location closer to the concave node, and hence less probable to resolve the local minimum. As a result of the above, the aggregate advantage offered by detouring repeated local minimum recoveries in GCRP is larger in denser networks. This is the dominant factor causing the increasing advantage of GCRP with respect to network density, which disagreed with initial intuition.

$$DM = E \cdot \sqrt{2}/R \quad (3)$$

GCRP performance also exhibits an increasing advantage as a function of network size (Figure 9). It is evident in medium and large networks, where the corresponding 95% confidence intervals are totally disjoint. In such networks, the average path length is larger, hence more local minimums are encountered (Figure 10). The overhead of the recovery process converges as the network size increases

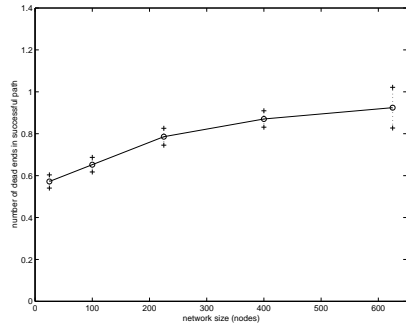


Figure 10. Number of dead ends in successful path vs. Network Size.

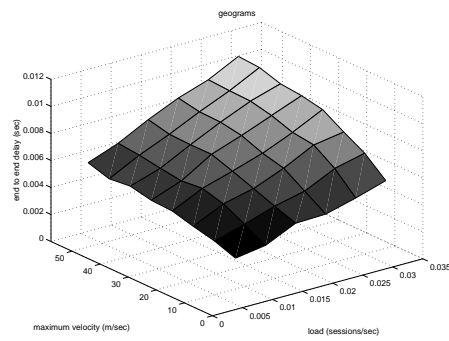


Figure 12. Geogram End-to-end delay vs. Traffic Load and Mobility.

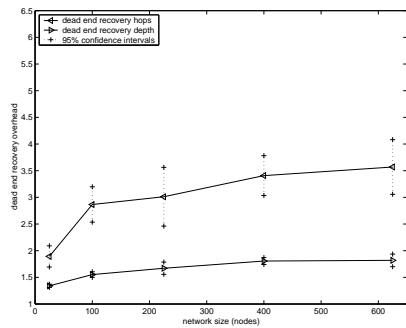


Figure 11. Local Minimum Recovery Overhead vs. Network Size.

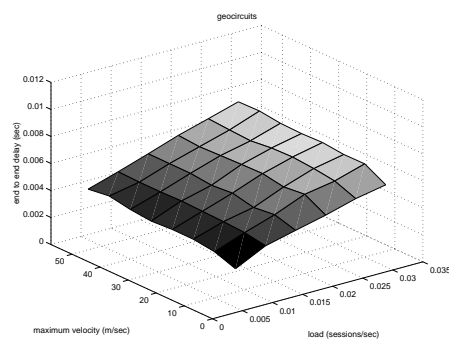


Figure 13. Geocircuit End-to-end delay vs. Traffic Load and Mobility.

(Figure 11), as it depends on network density and not network size. The overhead of successful local minimum recovery in small networks is lower because it is highly likely that a void falls partially outside of the network area boundaries.

As load increases, the aggregate performance of GCRP scales much better with respect to that of conventional geogram routing (Figures 12 and 13).

The decrease in the average end-to-end delay achieved by GCRP is coupled by an increase of the probability that packets are delivered to their final destinations (Figure 14).

The performance of GCRP showed an advantage with respect to that of conventional geogram routing. The gain increases as limiting network parameters are increased. GCRP exhibits scalable performance, while susceptibility to local minimums and local minimum recovery overhead increase, significantly degrading the performance of conventional geographic routing.

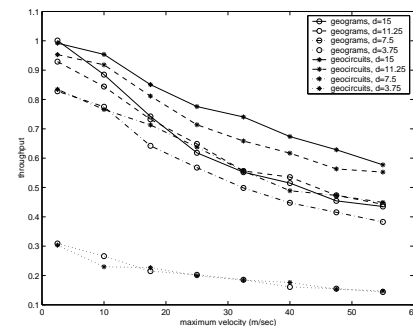


Figure 14. End-to-End Throughput vs. Network Mobility and Density.

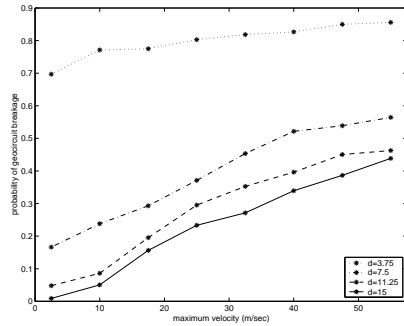


Figure 15. Probability of Geocircuit Breakage vs. Network Mobility, and Density

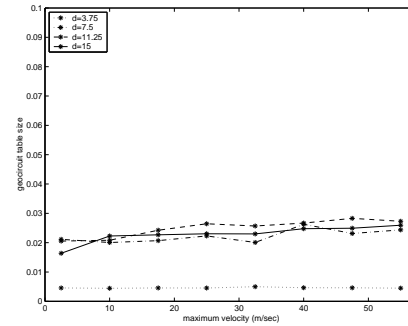


Figure 17. GC-Number Translation Table Size vs. Network Mobility, and Density

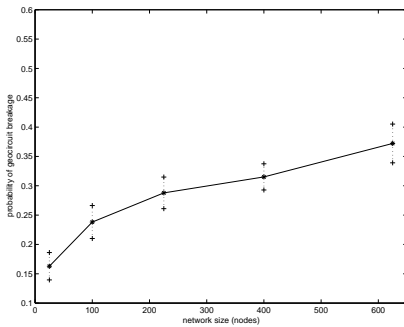


Figure 16. Probability of Geocircuit Breakage vs. Network Size.

5.2 Geocircuit Survivability

The performance of GCRP also depends on the effectiveness of geocircuit repair. The repair of broken geocircuits is immediate, requiring no additional delay before the data packet that encountered the breaking point can be routed further. However, repaired geocircuits may only be optimal in parts, where optimality is considered with respect to the forwarding criterion. For instance, in Figure 3(b) the novel sub-path from node *A* to the destination *D* may not be part of a globally optimal path from *S* to *D*, with respect to the distance minimization criterion.

The probability that a geocircuit breaks increases as a function of mobility (Figure 15), however this negative effect is out powered and does not invert the protocol performance. Note that geocircuit optimality (with respect to the forwarding criterion) is lost over time in mobile networks even if there is no breaks in circuits, as circuits are locally optimal only at the time that they are established.

The susceptibility to geocircuit breaks decreases as density increases (Figure 15), hence contributing to the scalable performance of GCRP. As network size increases, the probability that a geocircuit breaks increases (Figure 16), due to the longer average path length.

The scalable performance of GCRP with respect to network size and mobility verifies the effectiveness of the geocircuit repair.

5.3 GC-Number Translation Table Size

A form of overhead inherent in geocircuit routing that needs to be considered is the size of GC-tables. We observe that the average geocircuit size in number of entries (Figure 17) is small in sparse networks. In these environments the probability of network partitions is high. Loss of network connectivity leads to fewer and shorter available paths, as verified by the corresponding throughput and end-to-end delay observations (Figures 14 and 5). Hence fewer geocircuit mappings need to be maintained. When network density is higher, so that the probability of network disconnections is low, the path lengths are similar, as revealed by the corresponding delays. Hence the total geocircuit mapping information that needs to be maintained is comparable. As mobility increases, we expected the negative effect of stale information maintenance to be evident, due to higher susceptibility to geocircuit breakages (Figure 15). The increase in GC-table size is however very small, demonstrating that stale information is effectively discarded. As network size increases, the mean GC-table size decreases (Figure 18). As the network becomes larger while connectivity remains constant, the same traffic load is distributed in a larger number of nodes, hence fewer entries are maintained at each node. However, in large networks the paths are longer and hence the GC-table entries corresponding to a single session are more. This is why the decrease in the

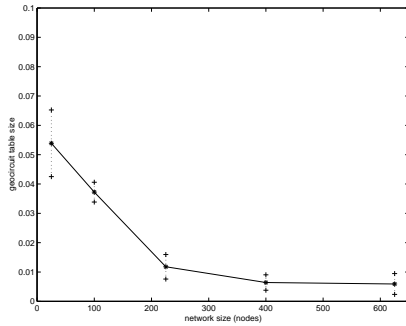


Figure 18. GC-Number Translation Table Size vs. Network Size.

GC-table size becomes milder as networks become larger. The GC-table size does not increase with a higher rate than network parameters reaching their limiting values. Hence, GCRP exhibits scalability in terms of the memory requirement.

6 Conclusions and Future Work

Geocircuits have been introduced to mitigate negative effects of the local minimum recovery process in geographic routing algorithms. They pursue this by caching the routing information acquired through the recovery process, to route subsequent packets. In this paper we specify GCRP, a geographic routing protocol that employs geocircuits to detour repeated local minimum recoveries. We propose a timely, low-cost geocircuit repair technique and introduce advances in our local minimum recovery scheme and mobility model. GCRP is established to be loop-free, while its routing tables maintain this property even in a mobile environment. It is compared to conventional geographic routing, wherein packets are routed independently as geograms. Results demonstrate that GCRP performs better in a wide range of network conditions, while the gains increase as limiting network parameters are increased. It may reduce the end-to-end delay up to 50% in highly mobile and dense environments. GC-number translation table size does not increase with higher rates than network parameters. Robust geocircuit repair allows for scalable performance when susceptibility to breaks is high.

Future research directions include investigation of different protocol design choices, as well as verification of results under different mobility patterns. Sensitivity to different location management schemes may be investigated by introducing further imprecision in the obtained destination location information.

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