Position-based Routing using Virtual Small World in MANETs

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***Abstract*— Routing is the foremost issue in mobile ad hoc networks (MANETs), In a wireless environment characterized by small bandwidth and limited computation resources, position-based routing is attractive because it requires little communication and storage overhead. To guarantee delivery and improve performance, most position-based routing protocols, e.g. GFG, forward a message in greedy mode until the message is forwarded to a node that has no neighbor closer to the destination. They then switch to a less efficient mode. Face routing, where the message is forwarded along the perimeter of the void, is one example. This paper tackles the void problem from a different angle. We construct a virtual small world network by adding virtual long links to reduce the chance of a protocol encountering local minima in greedy mode, and thus decrease the chance to invoke inefficient methods. Experiments show that this method effectively improves the performance of the greedy-face combinations in terms of average hop count.**

Keywords: position-based (geometric) routing, mobile ad hoc networks (MANETs), simulation, small world model

I. INTRODUCTION

A mobile ad hoc network (MANET) is comprised solely of wireless stations. The communication between source and destination nodes may require traversal of multiple hops because of limited radio range. Existing routing algorithms can be broadly classified into topology-based and position-based routing protocols. Topology-based routing determines a route based on network topology as state information, which needs to be collected globally on demand as in routing protocols DSR [7] and AODV [17] or proactively maintained at nodes as in DSDV [16].

The scope of this paper is focused on position-based routing, also called geometric or geographic routing. Position-based routing protocols are based on knowing the location of the destination in the source plus the location of neighbors in each node. They are attractive for MANETs for the following reasons: (1) they incur low route discovery overhead compared to flooding-based approaches in on-demand topology-based routing protocols, and hence save energy and bandwidth, and (2) they are stateless in the sense that nodes need not maintain per-destination information, and only neighbor location information is needed, either from a GPS [4] or through other means, to route packets.

Most position-based routing protocols use greedy forwarding as their basic operation. In greedy forwarding, a forwarding node makes a locally optimal greedy choice in choosing the next hop for a message. Specifically, if a node knows its neighbors' positions, the locally optimal choice of next hop is the neighbor geographically closest to the destination of the message. Greedy forwarding, however, fails in the presence of a void (also called a local minimum or a dead end) where the only route to the destination requires a packet move temporarily farther in geometric distance from the destination.

In order to recover from a local minimum, most existing protocols switch to a less efficient mode, such as the face routing mode. Face routing [3] (also called perimeter routing or planar graph traversal) on a connected network theoretically guarantees the delivery of packets. Face routing runs on a planar graph, in which the message is routed around the perimeter of the void (face) surrounded by the edges using the right-hand rule. Example of the existing greedy-face combinations are GFG [2], its variant GPSR [8] and GOAFR [11].

By observing simulations, we notice the following problem with the greedy-face combination. While a message always travels toward the destination in the greedy mode, it loses its direction in face mode. And in certain topologies, voids can lead to excessive retracing. This problem is mitigated by GOAFR [11], which restricts the traversal of the messages in face mode using a serial of eclipses increasing in size and effectively decreases the average route length.

Unlike GOAFR [11], this paper tackles the above problem from a different angle. The method is to construct a virtual small world network. Specifically, each node in the network has some remote contacts connected by *virtual long links* (VLLs). Each VLL consists of multiple consecutive physical links. To be scalable, the length (in hops) of the VLLs conform to a 2-exponent power-law distribution, which is analogous to [9]. The purpose of introducing VLLs is mainly to reduce local minima for a greedy routing and hence the chance of turning to face mode.

The VLLs reduce the chance of a greedy protocol encountering local minima from two aspects. First, VLLs give additional long connections to the nodes in the network. The effectiveness of VLLs in reducing local minimum can be see in Figure 1(a). In the figure, the number of local minima is averaged over the number of local minima for each node in the network. Second, when routing a message, VLLs is helpful for a greedy protocol to circumvent local minima ahead connected

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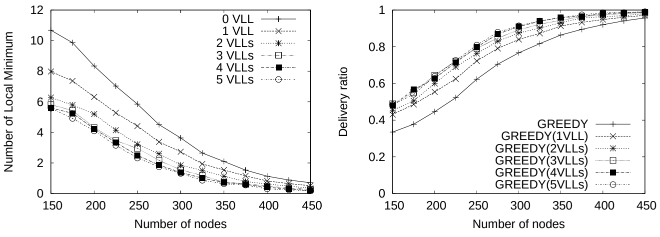


(a) (b)

Fig. 1. Effectiveness of the virtual long links in reducing the number of local minimum. 2 VLLs means 2 virtual long links per node (a) & Delivery ratio in pure greedy routing protocol (b).

through regular links. Further experiments show that the VLLs are able to increase delivery ratio in the greedy protocol and decrease the average route length in the greedy-face combinations. The rest of the paper is organized as follows. Section II briefly summarizes the related works. Section III presents our algorithm to construct the virtual small world network, which includes the construction and maintenance of the VLLs. Section IV presents our greedy routing algorithm in the virtual small world network. In Section V, we perform extensive simulations of the greedy-face routing protocols in our virtual small world network to analyze the effect of VLLs on reducing the average route length. Overhead and scalability of our algorithm is analyzed in Section VI. Finally, Section VII concludes the paper.

II. RELATED WORKS

Before turning to our technical content, we first put our work in context. Our algorithm is based on position-based routing and the small world model. In this section, we will briefly present the related works in those fields.

A. Position-based Routing

Localized algorithms are desirable in MANETs, in which nodes make routing decisions based only on the information about its neighboring nodes and the position of the destination. One such method, the greedy routing algorithm, in which each node forwards the message to its neighbor closest to the destination, is based on the location information supplied by GPS [4].

In *greedy face greedy* (GFG) [2] and its variant *greedy perimeter stateless routing* (GPSR) [8], when a packet reaches a region where greedy forwarding is impossible, the algorithm recovers by routing around the perimeter of the region. The right-hand rule is used to route around the face, which requires a planar graph. A graph in which no two edges cross is known as planar. The *relative neighborhood graph* (RNG) [20] and *Gabriel graph* (GG) [6] are two planar graphs.

In [5] Datta, Stojmenovic and Wu improved GFG based on the concept of dominating sets. They propose to run GFG routing on the internal nodes. The network of internal nodes defines a connected dominating set (CDS), and each node must be either internal or directly connected to an internal node.

An extension to GFG/GPSR, *greedy other adaptive face routing* (GOAFR) [11], avoids routing beyond some radius by branching the graph within an ellipse of exponentially growing size to achieve worst-case optimality and average-case efficiency in term of average route length.

GVG [15] has its face forwarding section run over arbitrary non-planar graphs by adding virtual nodes at the crosses of the links. Representative examples, however, show that GVG has large average route length.

B. The Small World Model

The small world model [14] corresponds to a phenomenon in a social network where any two people have “six degrees of separation”. More recently, it has been shown in [21] that this phenomenon is pervasive in many natural and artificial complex networks, and is captured by two measurements: small average path length and high clustering coefficient (defined as the average fraction of pairs of neighbors of a node that are also neighbors of each other).

Kleinberg [9] defined an infinite family of random network models that seek a simple framework that encapsulates the paradigm of Watts and Strogatz – rich in local connections, with a few long range connections. Rather than using a ring as the basic structure, it uses a 2-dimensional $m \times m$ grid and allows each node to have a directional long link to a remote contact with the distance in the r-exponent power-law distribution. [21] also proved that there is a unique “navigable” model ($r = 2$) within the family for which decentralized algorithms are bound by $O(\log^2 m)$. The extension to the navigable hierarchical network is discussed in [10].

Terminode [1] is based on the small world model that does not always forward packets directly towards the destination. In order to optimize routing in case of voids in the network topology, a node finds a list of remote contacts distributed all over the network, to which it maintains a good path. To find a route to the destination, a node asks its remote contacts that in turn ask their remote contacts, and so on. The right remote contacts found are added as a loose source path to the header of the data packets. Though Terminode finds short paths, it uses some sort of broadcast to discover routes and it does not guarantee delivery.

In [13] [19], the authors study the throughput capacity of hybrid MANETs, in which they investigate the use of limited infrastructure, in the form of wires, for improving the energy efficiency MANETs. Our model differs from theirs in that we use no infrastructure, and our model uses VLLs that consist of multi-hop physical links. Besides, this paper is focused on routing.

III. CONSTRUCTION OF THE VIRTUAL SMALL WORLD NETWORK

A. Assumptions

First we simplify our discussion with the following common assumptions: (1) We assume an ideal environment in which radio ranges of all nodes are exact and symmetric and that there is no packet loss, so that two radios within transmission range can always communicate. (2) We assume that all nodes know their own positions, either from a GPS device [4], if outdoors, or through other means. This assumption becomes more and more realistic with the advent of inexpensive and miniaturized positioning systems. (3) We assume a location registration and lookup service that maps node addresses to locations [12]. Queries to this system use the same geographic routing system as data packets. (4) Finally, we assume that all nodes are stationary or node movement is ignorable as in other literature. Although node mobility is one of the most important considerations in MANETs, we assume that the routing process is very fast relative to node movement.

B. Basic Ideas

In this section, we will present our method to construct a virtual small world network by adding a number of virtual long links (VLLs) to each node in the network such that the distance (in hops) to a remote contact is under the power-law distribution. Our method is that each node periodically sends out VLL discovery messages which go away and then come back to report a VLL. The first problem here is how to decide the maximum hops and the direction of a message. The second problem is how to select a subset of most valuable virtual long links when the storage in each node is limited.

C. Virtual Long Links

When a VLL message (message for short in this subsection) is sent by a node (initiator), the message should go in a different direction from that of the previous messages so that the messages can explore different parts of the network. Also, the maximum hops of a message should be appointed in such a way that the algorithm is scalable.

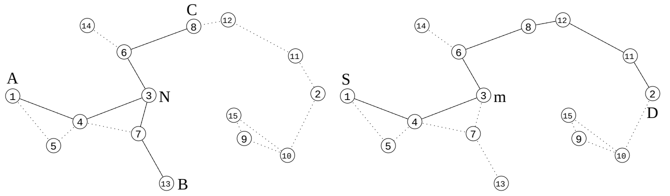
The maximum hops of a message is decided conforming to the power-law distribution as follows:

$$MaxHops = MinHops + \log_2(\frac{1}{p}) \tag{1}$$

Here p is a random value between 0 and 1, and $MinHops$ is a constant, which equals 2 in our experiment.

The reason for choosing the 2-exponent power-law distribution is two-fold. First, an analytical study in [9] shows that there is an analogous small world model (in an $m \times m$ grid) for which decentralized algorithms are bound by $O(\log^2 m)$. The second reason to use the 2-exponent power-law distribution is for scalability: only when $r \leq 2$ will the average VLL length converge.

It is desirable that each message chooses a random direction to go to explore different parts of the network. We use an imaginary point that is about 1-hop's distance away from the initiator of the message and the direction of the imaginary point to the initiator is chosen randomly. Then the message is let go and driven away by a virtual force (VF) from the imaginary point. This VF is inversely proportional to the distance between the imaginary point and the message's position. The message always tries to jump to the next node where it has a smallest force (e.g., the node farthest from the imaginary point).



(a) (b)

Fig. 2. The virtual long links of node N (a) & Pure greedy routing with virtual long links (b).

Not only should a message choose a random direction to go, it should preferably go to an area that has not been explored by earlier messages. Our method to accomplish this is to define a list of points that give VFs. This list includes the initiator, the imaginary point that gives a direction, and the endpoints of the VLLs established previously.

We define the VF between two points as:

$$force(a,b) = \frac{1}{1+d(a,b)} + \lambda e^{-\lambda d(a,b)} \tag{2}$$

The terms on the right side of the equation are not chosen randomly. The left term makes sure that the value of VF is not negligible from any distance and decreases smoothly as the distance between the points increases. The right term (with a big enough λ) makes sure that the force is extraordinarily big (which is equal to λ) when the 2 points overlap. This is used to prevent the VLLs from overlapping in their endpoints.

We define the composition of VFs (CVF) in a point n from a list L of points as the sum of the forces between n and each point L_i in the list.

$$force(n) = \sum_{0<i<|L|} force(n, L_i) \tag{3}$$

Assume that each node collects k-hops omni-directional link information, i.e. it maintains the omni-directional shortest paths to k-hops neighbor nodes. A message chooses its next hop on one of these omni-directional shortest paths which has the minimum force given a list L of points as the sources of the VFs. We define the force in a path P as the minimum force in the nodes on this path:

$$force(P) = \min_{0<i<|P|} force(P_i, R) \tag{4}$$

A message will stop exploring the network and come back to the initiator when its reaches the maximum hop count or when it goes into a local minimum under the CVF. The past traffic of a message is then reported as a new VLL. Figure 2(a) is an example of the VLLs in node N. Where $MinHops = 2$ and the number of long links is 3. In this example, the VLLs of node N in the random network is NA $(3,4,1)$, NB $(3,7,13)$ and NC $(3,6,8)$. We can see in the figure that the above algorithm can generate VLLs that lead to different areas of the network.

D. Evaluation of Virtual Long Links

We set an expiration time for each VLL considering that the continuously changing topology of the network may break some of the VLLs. Despite this, as a node periodically sends out VLL discovery messages, the required memory for the available VLLs can be larger than the limited storage in the node. Suppose the expiration time for a VLL is T_e and the time interval of sending consecutive VLL discovery messages is T_i, the maximum number of available VLLs is $k = T_e/T_i$. Roughly, if the storage limit is C_M VLLs and $C_M < k$, a node should discard $k - C_M$ less useful virtual long links.

Our replacement policy first lists all the possible combinations of C_M among k available VLLs and then calculates their usefulness. Only the VLLs in the set with the largest usefulness are retained. Our criterium of the usefulness of a set of VLLs is that the end points of the VLLs should be as far from each other and from the initiator as possible. The reason for this is that a node should have VLLs exploring different parts of the network in its vicinity (i.e., VLLs pointing to different directions) to make a forwarding decision for a message heading in any particular direction.

We found that entropy is suitable to measure the usefulness of a set of VLLs. Entropy is a measure of the internal microscopic disorder present in a system. Lets say a set of points are in disorder if they are not close in position, we can use entropy to evaluate the level of position discrepancy of the points. Hence the larger the entropy, the larger the level of discrepancy in the points' positions and the more useful is the set of points in our criterium.

Suppose G is a *Gaussian window function*, d is the *Euclidean distance function*, the Renyi's entropy [18] of a set of points V is defined as follows:

$$G(a,b) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{d(a,b)}{2\sigma^2}} \tag{5}$$

$$Entropy(V) = -\ln \frac{\sum_{0<i<|V|} \sum_{i<j<|V|} G(V_i, V_j)}{\frac{|V|(|V|-1)}{2}}, \tag{6}$$

IV. ROUTING IN THE VIRTUAL SMALL WORLD NETWORK

Extending the greedy protocol using VLLs is straightforward. The set of paths used in the new protocol contains the shortest path to all neighbor nodes and all VLLs. In the new protocol, the distance between a path and the destination is defined to be the minimum distance of the nodes on the path. The greedy protocol with virtual long links is shown below as Algorithm 1. An example of this routing protocol is shown in Figure 2(b), where a message is sent from the source S to the destination D successfully. While a traditional greedy algorithm will fail on the local minimum m, our algorithm succeeds, since there is a VLL NC $(3, 6, 8)$ through which a message in m knows that node number 8 is closer than m (3) to D. That is, the local minimum m is circumvented by the VLL NC.

Algorithm 1 Greedy protocol with virtual long links

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List the paths which contain the shortest path to all neighbor nodes and all virtual long links.
Calculate the distances of these paths to the destination.
Send the message to the next node on the path with the smallest distance.
Repeat the above steps until the message gets to the destination, a local minimum, or the maximum hop count.
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The above protocol might cause a loop. Suppose there is a VLL (A, B, C) that is the best path for destination D when a message is in A, and there is also a VLL (B, A, E) that is the best path for destination D when a message is in B. When a message travels to A or B, a loop $(A, B, A \ldots)$ will begin.

There is a simple solution to this problem, but with several bytes of additional transmission overhead: a message carries the path that it is currently being forwarded on and lets the next node on the path consider the path in its forwarding decision. We show how this method works still using the last example. Suppose C is closer than E to D. When a message is forwarded from A to B, it carries the path (B, C). Thus when B makes a forwarding decision for the message, the path (B, C) will be chosen instead of (B, A, E), and thus the loop is removed. In the following we will prove it formally.

Lemma 1: If a message M carries its current path, and M travels from node A to node B through a serial of path $P_1, P_2, \ldots, P_n$, and B is the end of P_n, then the distance $d(A, D) > d(B, D)$, where D is the destination of M.

Proof: Suppose $s_1, s_2, \ldots, s_n$, $e_1, e_2, \ldots, e_n$ are the starting points and the end points of the paths $P_1, P_2, \ldots, P_n$ respectively. We have $d(s_1, D) > d(e_1, D)$. And since in each s_i for all $2 \leq i \leq n$ the message chooses e_i instead of e_{i-1}, we have $d(e_i, D) < d(e_{i-1}, D)$. Therefore $d(A, D) = d(s_1, D) > d(e_1, D) > d(e_2, D) > \ldots > d(e_n, D) = d(B, D)$. ■

Theorem 1: If a message M carries its current path, the greedy protocol with virtual long links is loop free (temporary loop is not counted).

Proof: To prove *Theorem 1*, we need to prove that a message M will not travel to any node A infinite times. Suppose P_i is the path with minimum distance to destination D when M is in A for the i-th time, and e_i is the end point of P_i. According to Lemma 1, we have $d(e_1, D) > d(e_2, D) > \ldots > d(e_n, D)$. Since the number of nodes in the network is finite, the number of e_i is finite. Therefore, M will not travel to A infinite times. ■

V. SIMULATION

In this section we compare the performance of greedy-face combinations routing in pure MANETs with that in virtual small world MANETs. Since a virtual small world MANET has VLLs that need additional overhead to construct, it is not fair to compare the performance in pure MANETs and in virtual small world MANETs directly. The purpose of this section is to investigate the benefit of constructing a virtual small world MANET if VLLs can be add to a MANET. We use the average route length as the criterium to quantify the benefit of introducing the VLLs.

A. Simulation Environment and Settings

We make the following assumptions in our simulation: (1) the MAC layer is collision free and the transmission delay is constant, (2) all the position information required is available without additional communication overhead, and (3)

Algorithm Name	G	F	CDS	VLL	BE	SB
GREEDY	√					
GREEDY(VLL)	√			√		
GFG	√	√				√
GFG(VLL)	√	√		√		√
GFG(CDS)	√	√	√			√
GFG(VLL+CDS)	√	√	√	√		√
GOAFR	√	√			√	√
GOAFR(VLL)	√	√		√	√	√
GOAFR(CDS)	√	√	√		√	√
GOAFR(VLL+CDS)	√	√	√	√	√	√

TABLE I
CLASSIFICATION OF THE SIMULATED ROUTING ALGORITHMS

the routing process is very fast compared to node movement, and node movement was not simulated. Simulations were conducted on three protocol families: the Greedy family, the GFG family and the GOAFR family. Table I shows them (in rows) and the algorithms used in each protocol (in columns). These algorithms include the Greedy algorithm (G), the Face algorithm (F), the connected dominate set (CDS) used in face mode [5], the virtual long link (VLL) in Greedy mode, bound eclipse in GOAFR [11] and the sooner back algorithm [5] (the face mode returns sooner back to the greedy mode if the current node has a neighbor closer to the destination than the last local minimum).

The metrics we use to evaluate the protocols are delivery ratio and average hop count. Delivery ratio is the ratio of the number of messages delivered successfully to the destination over the total amount of message sent. The average route length is counted in terms of physical hops. There are two reasons for choosing the hop metric for our simulations. First, the hop metric is a model for today's radio network technology: fixed power. Second, [11] shows that the Euclidean distance, the link distance, and the energy metrics of a path are equal up to a constant factor on the unit disk graph.

We do the simulation on our custom simulator. In each experiment a connected graph with N (ranging from 150 to 450 in different experiments) nodes is randomly generated in a 1000×1000 square. After that, we let the simulator run for a period of time which is sufficient for the nodes to grow the virtual long links. Then, for each node, messages are added to be sent in the routing protocols listed in Table I. The destination of these message is another node chosen randomly. We run each experiment 100 times to get the average value. The network density in our experiment ranges between two extremes. The sparse extreme is the only region where the shortest path is usually much longer than the direct connection between the source and the destination. This region is critical for routing algorithms, where finding a good path at low cost becomes a nontrivial task and a real challenge for position-based routing. In the dense region, all algorithms have similar performance since they all degrade to pure greedy. All the important parameters in our simulation are shown in Table II.

Parameter	Value
Field size	1000×1000
Transmission range	100
Transmission delay	10(ms)
Number of nodes	$150 \sim 450^*$
Network degree	$4.71 \sim 14.13$
Max routing hops count	$(*)$
Number of VLLs	$0 \sim 5$
Minimum length of a VLL	2
Time run for VLLs	10000(ms)
Time for running routing	$(*)$×10(ms)

TABLE II
EXPERIMENT SETTINGS.

B. Simulation results

Figure 1(a) shows that the number of local minima decreases as the number of VLLs per node increases. Figure 1(b), show that the delivery ratio of the pure greedy routing protocol increases as the number of VLLs increase. Figure 3 and Figure 4 show that the average route length of the two greedy-face combination decrease as the number of VLLs per node increases. In all these figures, the effect of the number of VLLs is only significant before 3, thus we have the conjuncture that using 3 VLLs can approximate using more than 3.

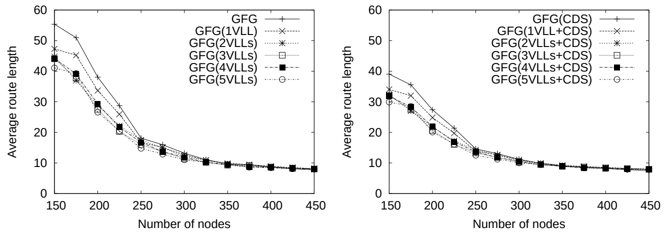
To summarize the simulation, the VLLs are able to improve the performance of the greedy-face combinations by decreasing the average route length. If possible, more VLLs may be kept in order to better improve the performance.

VI. OVERHEAD & SCALABILITY ANALYSIS

In this section, we measure the scalability of our algorithm by calculating the computation overhead, storage overhead and communication overhead. Since the average distance between a pair of nodes increases as the network diameter increases, which makes routing not scalable, we do not consider the communication overhead of routing in our analysis. From the following analysis, we show that our algorithm is scalable for its very little additional overhead.

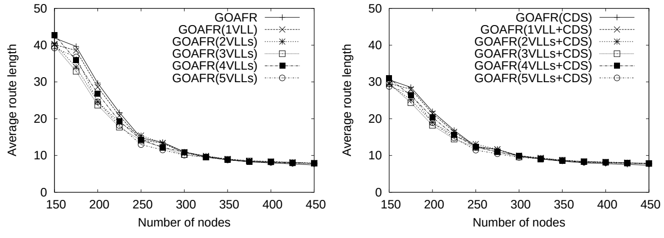
First, we discuss the gathering of omni-directional link information without relying on the underlying hardware. If a node needs information of k-hops omni-directional links, they need to have their $k+1$-hop directional links and disseminate their k-hops directional links. Let D be the maximum degree in the network. The number of k-hops ($(k+1)$-hops) directional links is $O(D^k)$ ($O(D^{k+1})$). Therefore, the amortized communication overhead per hello message interval is $O(D^k)$ and the memory overhead is ($O(D^{k+1})$). When 1-hop omni-directional links are used as in our simulation, the communication overhead is $O(D)$ and the memory overhead is ($O(D^2)$).

Since the length of a virtual long link is in power-law distribution $p(MaxHops) = 1/(MaxHops - MinHops)^2$, the expectation of the length of the virtual long link is $MinHops + 1$. Therefore the amortized communication overhead for establishing virtual long link overhead per VLL message interval is $O(MinHops+1)$. There are two different ways of implementing long links: (1) quick establishment in



(a) (b)

Fig. 3. Average route length in GFG.



(a) (b)

Fig. 4. Average route length in GOAFR.

which long links discovery messages are relayed instantly and the communication overhead is reflected in the number of transmissions, and (2) slow establishment (by integrating it in Hello messages) in which the addition of communication overhead is just a few more bytes in each hello message. But the slow establishment is only applicable if the network is relatively static.

The computation overhead for establishing virtual long links is the computation overhead of the entropies as discussed in Section III-C. Assume the entropies are calculated whenever the number of virtual long links exceeds the memory capacity C_M. The computation overhead is $O(C_M^3)$ ($O(C_M)$ for the number of combinations and $O(C_M^2)$ for the entropy of each combination).

In the greedy routing in virtual small world networks, besides storing the ID and the position of the destination ($O(1)$ memory overhead), a node need only store the k-hops omni-directional links and the VLLs. Let C_M be the number of VLLs that can be stored in each node. The per-node memory overhead is $O(D^k) + O(C_M)$.

In Section 1 the computation for making the message forwarding decision includes listing all the shortest path to k-hops neighbors and calculating the virtual force of each path given a repulsive list R. The computation overhead for message forwarding is $O(D^k \cdot |R|)$.

VII. CONCLUSION

The paper has presented a research in position-based routing in mobile ad hoc networks. This paper solves the problem of the suboptimal that arises from void-recovery protocols. Rather than attempting a more optimal face-routing protocol, we improve routing from a different angle. We propose an improvement on the greedy algorithms that reduces the number of local minima, thus reducing the amount of time that must be spent in sub-optimal void recovery protocols. We do this by constructing a virtual small world network. Simulation results show that this method effectively improved the performance of the greedy-face combinations in terms of average hop count. Our future work will focus on the simulation in a real dynamic network where part of the long links might be broken due to node motion.

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