# Logical Location-based Routing with Hole-shadowing in Large-scale MANETs

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***Abstract*---The Virtual Dynamic Backbone (VDB) is proposed in the infrastructure-less Mobile Ad hoc NETworks (MANETs) to seek for similar capabilities of the high speed and broadband backbone in the Internet. In this paper, we propose a logical mesh-based VDB model, which is a highly stable hierarchy of mobile nodes with multi-level radios for wireless transmissions. Based on the proposed model, a logical-location-based routing algorithm combining topology-based routing and location-based routing is proposed. The proposed algorithm uses a novel hole-shadowing-based forwarding strategy in order to avoid holes in the network. The comparative analysis shows that the proposed algorithm outperforms the well-known routing algorithm called GPSR in terms of tolerating the location inaccuracy and communication complexity, with a little larger cost of control complexity. Simulation results show that the proposed algorithm achieves short routing delay, which is a prerequisite to achieve the scalability.**

***Index Terms*---Mobile ad hoc networks, routing, logical location, virtual dynamic backbone**

## I. INTRODUCTION

Mobile Ad hoc NETworks (MANETs) is a very hot research topic in recent years due to their self-organizing, rapidly deployable, dynamically reconfigurable properties. There are two kinds of structures in MANETs: flat and hierarchical. The hierarchical structure scales very well. It can be further categorized into single-level radio hierarchy and multi-level radios hierarchy. In the former, all the Mobile Nodes (MNs) use the same radio; while in the latter, MNs in different tiers use different radios, higher-tier MNs have multi-level radios with different transmission ranges, and these radios operate in different frequency spectra.

Routing protocols in MANETs can be categorized into two classes: topology-based and location-based. The former uses the network topology information to compute and maintain routes, while the latter uses geographic location information to help decide the next-hop routing. In location-based routing, people usually assume that a link exists as long as a node resides in the transmission range of another node.

The Virtual Dynamic Backbone (VDB) [6] is a sub-graph of the entire network topology, which is proposed in MANETs to seek for similar capabilities of the high speed and broadband backbone in the Internet in supporting efficient data transportation. The utilization of the VDB exploits a hierarchical structure and makes it easy to extend to large-scale MANETs.

This paper proposes a two-tier logical Mesh-based VDB (MVDB) model, where the Cluster Heads (CHs) have two-level radios, namely, the radio with short transmission range (i.e., short radio) for communication among cluster members, and the radio with long transmission range (i.e., long radio) for communication between adjacent CHs. Based on the MVDB model, a scalable logical-location-based routing algorithm is proposed, which is a hybrid of topology-based routing and location-based routing. The proposed algorithm uses the logical location to identify an MN in the sense that it is actually the identity of the Virtual Circle (VC) [12] region where the MN resides. The proposed algorithm uses a novel hole-shadowing-based forwarding strategy to avoid holes in the network, so as to prevent the algorithm from terminating with a local optimum, a situation usually occurring in location-based routing.

The motivations for us to use a mesh-based scheme and multi-level radios in the MVDB model are as follows: (1) The mesh-based scheme is resilient to link failures for its multiple paths between nodes in order to improve the reliability of the proposed protocol. (2) With two-level radios, the CHs can perform most of the protocol tasks and the cluster members can be kept very simple in order to improve the scalability of the proposed protocol.

The remainder of the paper is organized as follows. Section II gives an overview of routing protocols in MANETs. The proposed MVDB model is introduced in Section III. Section IV describes the proposed routing algorithm. Section V&VI present the comparative analysis and simulation studies respectively. Section VII concludes this paper.

## II. RELATED WORK

In general, topology-based routing protocols can be further classified to be proactive or reactive. A proactive routing protocol periodically updates the routing table of each node so as to maintain the network topology, while a reactive routing protocol searches for a path in an on-demand manner.

A typical proactive protocol is Destination-Sequenced Distance-Vector routing (DSDV) [9], where each node maintains routing table for all available destinations, and periodically broadcasts its routing table, and broadcasts updates immediately when its routing table changes. DSDV adds sequence numbers to routing updates on the basic Bellman-Ford routing mechanism, in order to avoid possible routing loops. DSDV is relatively simple, but not adaptive to the highly changing network environment.

A typical reactive protocol is Dynamic Source Routing (DSR) [3], which generates routing overhead only when necessary. A source node floods a route request throughout

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the network. When the request reaches the destination, the destination returns a route reply. In addition, nodes aggressively cache routes, so that intermediate nodes can reply to the request on behalf of destination nodes. Location-Aided Routing (LAR) [4] is an optimization of DSR, where nodes restrict the propagation of route request packets to the geographic region where the destination most probably resides. In this protocol, geographic location is used not for making the forwarding decisions on data packets, but for restricting the propagation of control packets. This protocol greatly reduces the routing discovery overhead induced in DSR.

A survey on location-based routing protocols can be found in [8], where a qualitative comparison of the existing protocols is provided. Paper [11] also gives a deep analysis of known location-based routing methods, such as GEDIR, DIR, and MFR algorithms. It proposes a modification called 2-hop GEDIR, DIR, and MFR methods to all three basic algorithms, in which each node selects the best candidate node among its 1-hop and 2-hop neighbors. It also proposes flooding GEDIR and MFR and hybrid single-path/flooding GEDIR and MFR methods which are the first localized algorithms (other than full flooding) to guarantee the message delivery.

Terminode routing [2] uses geographic location information. It includes two parts: Terminode Local Routing (TLR) which forwards packets to destinations based on local routing tables in two-hop vicinity, and Terminode Remote Routing (TRR) which uses a greedy forwarding approach to send packets to remote destination on anchored path. The anchored path is a list of fixed geographic points and is obtained from *friends* based on the concept of small world networks [14]. Terminode routing simply assumes that there exists an implementation of the concept, but it is very difficult to implement such a concept in MANETs.

GRID [7] is also location-based, which divides the geographic network area into a number of logical square grids. Routing is then performed in a grid-by-grid manner through grid leaders. Since it uses the location of a grid which does not change over time, other than an MN's location which changes from time to time, it lengthens the lifetime of routes. But it confines relay nodes to grid leaders, thus has higher hop counts, i.e., larger delay, compared with LAR which tries to search routes with the smallest hop counts.

Greedy Perimeter Stateless Routing (GPSR) [5] makes greedy forwarding decisions using only location information about a node's immediate neighbors. When a packet reaches a region where greedy forwarding is impossible, the algorithm recovers by routing around the perimeter of the region.

Routing protocols in MANETs can benefit from a stable VDB structure since the number of nodes involved with the routing can be reduced to that of the backbone nodes. LANMAR [16] routes on a VDB structure. The VDB nodes are dynamically grouped into multi-hop clusters. Each group elects a CH to be a VDB node. Then higher-level links are established to connect the VDB nodes by the longer-range radios. It extends the original LANMAR in [10] by operating on the multi-level radios hierarchy. The hierarchical Landmark routing algorithm introduced greatly reduces the number of routing hops.

## III. THE LOGICAL MESH-BASED VDB MODEL

This section introduces a logical Mesh-based VDB model (MVDB) shown in Fig.1. In the model, the large-scale MANET is deployed in a rectangular region, which is divided into square regions of equal size. Based on these square regions, Virtual Circles (VCs) of equal size can be formed, which overlap with each other in a systematic way, as in [12], are formed Each VC takes the center of a square region as its center, and the diagonal of the square region as its diameter. The center of a VC is called a Virtual Circle Center (VCC).

In Fig.1, the Mesh Tier (MT) is drawn in circle regions, and the MN Tier (MNT) isn't drawn in circles for clarity. The MVDB has the *non-virtual* and *non-dynamic* properties, which are similar to *reality* and *stability* properties of the backbone in the Internet respectively: (1) To realize the non-virtual property, we assume that each MN can acquire its location information by a GPS or some localization algorithm. Thus each MN knows the non-virtual VC it belongs to. (2) To realize the non-dynamic property, i.e., to form a stable MVDB, we assume that the MNs have different computation and communication capabilities, with the *super MNs*, i.e., both current CHs and candidate CHs, having stronger computation and communication capabilities (especially two-level radios) than the *normal MNs*, i.e., the normal cluster members. We argue that this is reasonable in practice, e.g., in a battlefield, a mobile device equipped on a tank can have stronger capability than the one equipped for a foot soldier.

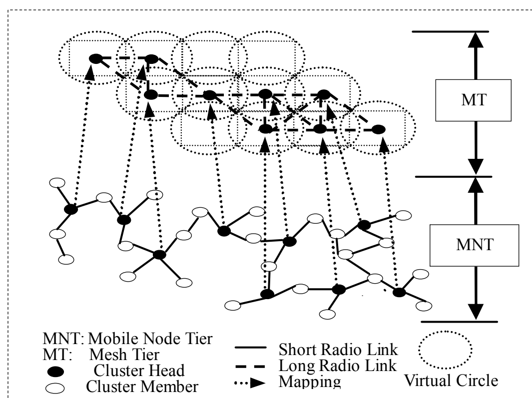


**Fig.1. The Logical Mesh-based VDB Model**

The MNT consists of MNs in the network. The MNs that reside in the same VC are grouped into a cluster according to the (*p*, *t*, *d*)-clustering algorithm in [12], which is shown to be able to form stable clusters. The clustering algorithm uses two criteria to elect a CH in a VC: (1) the CH is closest to the VCC, and (2) the CH stays alive the longest time in the VC. Here, we add one more criterion that a CH should be a super MN. The CHs are responsible for communicating between clusters and managing their member nodes. They form the backbone nodes.

The MT is a 2-dimensional mesh network, by viewing each CH as a mesh node. A mesh node can communicate directly with its 8 adjacent mesh nodes by using long radios. A mesh node becomes an actual one only when a CH exists in the corresponding VC. If not, then the mesh node is empty. We assume a uniform distribution of super MNs, so it seldom occurs that some normal MNs exist in a VC but no super MNs exist in it. When this case does occur, those normal MNs will try to find proxy CHs in their neighboring VCs.

Both CHs and cluster members use the transmission range $r$ of short radio for intra-cluster communication. The transmission range $R$ of long radio is used only by CHs for inter-cluster communication. It is easy to see that the diameter $d$ of a VC satisfies $d \geqslant 2r$. As shown in Fig.2, we assume that the relation between $R$ and $d$ satisfies $R = 3/2\, d$ , so that a mesh node, if the CH resides at the center of a VC, can communicate directly with its 8 adjacent mesh nodes.

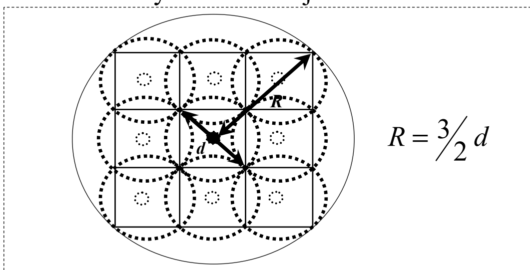


**Fig.2 Relation of *R* and *d***

## IV. The Logical-Location-based Routing Algorithm

The proposed logical-location-based routing algorithm uses topology information for local routing and logical location information for remote routing. We assume that the source node knows the location of the destination node via some location service, such as home region-based location service [15] and multiple home regions based location service [13].

All the MNs know some system parameters: the total number of MNs $N$, network width $W$, network length $L$, network center coordinate ($x_c$, $y_c$), diameter of VC $d$. Then the coordinate of the network origin point ($x_o$, $y_o$) is $\left((x_c - L/2), (y_c - W/2)\right)$, the side length of small square region is $\sqrt{2}/2\, d$ , and the total number of VCs is $2WL/d^2$ .

Two identifiers are given: MNID is the global identifier of an MN, which is given at the system start-up time, and VCID is the identifier of a VC. The VCID can be considered as the *logical location* for each MN that resides in the VC. Each MN can determine its logical location by Definition 1 according to its coordinate. An MN's corresponding VCID changes less frequently than its geographic location. Thus the use of logical location makes the routing path very stable.

**Definition 1:** Suppose the coordinate of a VCC is ($X$, $Y$), the VCID can be labeled by two integers:

$$\left\lfloor \sqrt{2}(X-x_o)/d \right\rfloor, \left\lfloor \sqrt{2}(Y-y_o)/d \right\rfloor \qquad \dots (4.1)$$

### A. Local Routing

Two kinds of routing tables are maintained. The fist is the intra-cluster routing table. In a cluster, each cluster member periodically broadcasts a message with its MNID, geographic location and current time stamp to the CH, then the CH computes the routing table of the cluster and broadcasts this information to each cluster member. If the CH hasn't received a cluster member's information for a certain time, it will delete the information about the cluster member from the routing table.

And the other is the inter-cluster routing table. Each CH broadcasts a message with its MNID and logical location (i.e. VCID) and current time stamp in the vicinity of $k$-hop long transmission range. The CH receiving this message will forward it to the neighbors within the vicinity. Then each CH maintains an inter-cluster routing table of CHs in its $k$-hop vicinity defined by the long radios (here we assume a small $k$, such as 2, 3, or 4). A CH will transfer the two kinds of routing tables to a candidate CH before it moves out of the VC.

When a source node $S$ sends packets to a destination node $D$, if $S$ is a cluster member, it firstly sends packets to its CH. The CH checks whether $D$ is within its $k$-hop vicinity. If yes, it sends packets to the destination CH by using the $k$-hop vicinity routing table. Then the destination CH sends the packets to $D$ based on the intra-cluster routing table; otherwise, remote routing is needed.

### B. Remote Routing

Remote routing consists of two parts: greedy forwarding similar to GPSR [5] which is used whenever possible, and the proposed hole-shadowing-based forwarding which is used to deal with holes in order to prevent from reaching a local optimum. A local optimum indicates a situation where an intermediate node has no neighbor with progress toward the destination, while a valid route to the destination still exists. Here a *hole* is a small "desert", where no MNs exist.

Mesh nodes adjacent to the hole know the hole information by message broadcasting. If a mesh node hasn't received a neighbor's information for a certain time, it considers that the corresponding VC is empty. Then it broadcasts this hole information to other mesh nodes in its $h$-hop vicinity, just as the broadcasting in the inter-cluster routing. Here $h$ denotes Recovery Strength (RS), which defines the hop count between the farthest CH and the current CH within which the information is forwarded. The regions where those hole-aware mesh nodes reside look like a shadow of the hole, and the *hole-shadowing-based forwarding* is thus named.

The main idea of the hole-shadowing-based forwarding algorithm is as follows. If an intermediate mesh node knows some hole information, then it determines whether it is likely to meet a local optimum. If yes, it selects the next hop node of the shortest geographic distance to the destination, among the neighbors which are not in the direction of the hole, based on the hole information, until it is not likely to reach a local optimum. Then, greedy forwarding is performed again. That is to say, the first thing is to avoid the holes; then the shortest distance is considered. The detailed description is listed by taking Fig.3 as an example.

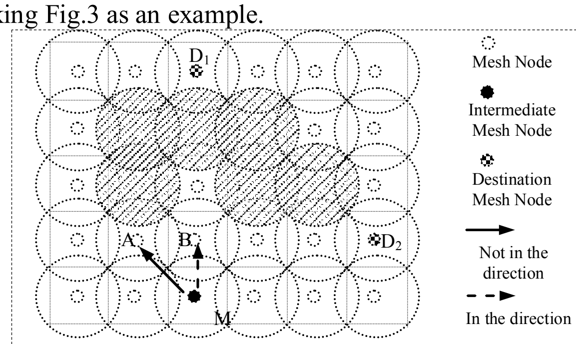


**Fig.3 Determination of the Direction of the Hole**

In Fig.3, $M$ is an intermediate mesh node that has the hole information, and $D_1$ and $D_2$ are two destination mesh nodes.

Assume that the center of VC that $D$ resides is $(X_D, Y_D)$. The VCC of $M$ and the next hop node are $(X_M, Y_M)$ and $(X,Y)$ respectively. The decision on whether there is a possibility of local optimum, or whether a next hop node is in the direction of the hole is made as follows.

(1) Calculate the line equation decided by the VCC of $M$ and $D$:

$$f(t) = \frac{(Y_M - Y_D)}{(X_M - X_D)} * t + \frac{(Y_M * X_D - Y_D * X_M)}{(X_D - X_M)} \quad \ldots (4.2)$$

(2) For each empty VC contained in the hole information, suppose its VCC coordinate is $(x_e, y_e)$, putting the coordinate into Formula 4.2, we get:

$$\left| \frac{(Y_M - Y_D)}{(X_M - X_D)} * x_e + \frac{(Y_M * X_D - Y_D * X_M)}{(X_D - X_M)} - y_e \right| < \frac{\sqrt{2}}{4} d \quad \ldots (4.3)$$

$$(X_D - x_e)(x_e - X_M) > 0 \quad \ldots (4.4)$$

Formulae 4.3 and 4.4 are used to determine whether the direct path from current node to the destination crosses any empty VC or not. Here, $\frac{\sqrt{2}}{4} d$ is the half of the small square region's side length.

(3) If any of the empty VCs satisfies Formulae 4.3 and 4.4 at the same time, it means that the direct path crosses the empty VC; thus it is likely to meet a local optimum, then hole-shadowing-based forwarding is performed; otherwise, a local optimum does not exist, and greedy forwarding is continued. For example, in Fig.3, to destination $D_1$, $M$ performs hole-shadowing-based forwarding; while to destination $D_2$, $M$ continues greedy forwarding.

(4) In the situation of destination $D_1$, first we get the line equation decided by the VCC of $M$ and the next hop node. Then for each empty VC contained in the hole information, based on the line equation, compute Formulae 4.5 and 4.6, to determine whether there is any empty VC in the direction from current node to the next hop node.

$$\left| \frac{(Y_M - Y)}{(X_M - X)} x_e + \frac{(Y_M * X - Y * X_M)}{(X - X_M)} - y_e \right| = 0 \quad \ldots (4.5)$$

$$(X_M - X)(X - x_e) > 0 \quad \ldots (4.6)$$

(5) If any of the empty VCs satisfies both Formulae 4.5 and 4.6 at the same time, the next hop node, such as node $B$ in Fig.3, is in the direction of the hole; otherwise, the next hop node, such as node $A$ in Fig.3, is not in the hole direction.

At last, the remote routing algorithm can be described as follows. $S$ first computes the logical location of $D$ based on its location information. Then $S$ sends packets to its CH. Thus, greedy forwarding is performed until hole-shadowing-based forwarding is needed. When leaving the possibility of local optimum, greedy forwarding is resumed. This is repeated until a CH finds that $D$'s VCID is within its $k$-hop vicinity. Then local routing is performed. The pseudo code of our remote routing algorithm is shown in Fig.4.

A proper value of $h$ is essential to reduce the control overhead, which can be determined by the size and the shape of holes. For example, if there is only one empty VC in a region, it is not necessary to propagate this hole information. That is, $h$=0 is feasible. In contrast, if holes are very large and their shape is complicated, a relatively large $h$ is needed. It is an interesting issue how to efficiently get an outline of a hole and then determine the value of $h$. We will investigate this problem in our future work. In this paper, we assume that $h$ is relatively small, such as 2, 3 or 4, in order to avoid causing too much control overhead.

```
The remote routing Algorithm.
If S needs to send packets to D Then
Do { S computes the VCID where D resides;
    If S is a cluster member Then
        It sends packets to its CH;
    Do {Greedy forwarding;
    } Until an intermediate CH has the hole information;
    If a local optimum is possibly met Then
        While the local optimum is still possible Do
         { It computes the distance to D among the
              neighbors that are not in the direction of the
              hole;
           It selects a next hop node of the shortest distance
              to D among those neighbors;
           }
    Do {Greedy forwarding;
       }Until a CH finds the VCID in its k-hop vicinity;
    Local routing is performed;
} Until the packets reach the destination D.
```

**Fig.4 The Remote Routing Algorithm**

## V. PERFORMANCE ANALYSIS

This section analyzes the performance of the proposed logical-location-based routing algorithm in comparison with GPSR. The face-2 algorithm [1] and the perimeter forwarding stateless algorithm called GPSR [5] are currently the most advanced recovery strategies. GPSR uses the right-hand rule to deal with holes when a local optimum occurs, while our hole-shadowing-based forwarding tries to avoid reaching a local optimum so as to eliminate unnecessary delay caused by the former. Three definitions are given below.

**Definition 2:** The communication complexity is the average number of one-hop transmissions required to send a packet from source to destination under the assumption that the location information of the destination is known.

**Definition 3:** The node density $\gamma$ is defined in terms of square meters per node. Then: $\gamma = WL/N$. … (5.1)

**Definition 4:** The control complexity is the total number of control messages required to prepare information for sending a packet from the source to the destination under the assumption that the location information of the destination is known.

**Theorem 1:** The proposed algorithm achieves a higher degree of tolerance of location inaccuracy than that in GPSR.

**Proof:** The evaluation in [5] shows that GPSR performs well with regard to the packets delivery success rate and the routing overhead. However, a big drawback of GPSR is that location information of the destination needs to be known with an accuracy of a one-hop transmission range; otherwise, the packets cannot be delivered successfully. While the usage of local routing tables in the proposed algorithm not only simplifies the routing, but also provides higher degree of tolerance of location inaccuracy with a $k$-hop long radio transmission range. □

**Theorem 2:** The communication complexity of the proposed algorithm is $O(\sqrt{N}/d)$, which is better than that of $O(\sqrt{N})$ for GPSR.

**Proof:** As the network grows larger, the number of hops between each pair of source and destination may also increase. If $\gamma$ is constant, then the average path length is expected to increase with the spatial diameter of the network, or equivalently the square root of the area of the network. Since the total number of MNs $N$ is in proportion to the network area, the communication complexity in GPSR is $O(\sqrt{N})$. But in the proposed algorithm, routing is mainly at the mesh nodes, and the maximal number of the mesh nodes is $2WL/d^2$ (there may be empty VCs without CHs). Then the communication complexity is $O(\sqrt{WL}/d)$, which can be simplified to $O(\sqrt{N}/d)$, because the network area is $WL$. □

**Theorem 3:** The control complexity of the proposed logical-location-based algorithm is:

$$O((1+8\gamma k(k-1)/d^2)N)$$

It approximates to $O(N)$ of GPSR.

**Proof:** Let $C$ be the number of CHs in the network. The control complexity of the proposed algorithm includes three parts corresponding to the following three phases:

*Phase* 1: The maintenance of intra-cluster routing table. Since each cluster member broadcasts a message to its CH, there are $(N–C)$ cluster members, then $(N–C)$ messages are needed. Assume that the probability of the reelecting of CHs is $\iota$, which is very small due to the stable ($p$, $t$, $d$)-clustering algorithm we used. The number of transferred messages from one CH to another CH is $C\times\iota$. At this phase, the total number of messages is:

$$N - C + C\iota = N - C(1-\iota) \approx N - C \quad \ldots (5.2)$$

*Phase* 2: The maintenance of inter-cluster routing table. Each CH broadcasts a message in the vicinity of $k$-hop long transmission range. Since each CH is assumed to be able to directly communicate with its 8 adjacent CHs, then almost 8*(1+2+…+($k$-1))=4$k$($k$-1) CHs need to forward the message except those empty VCs. So, at most 4$k$($k$-1)+1 messages are needed for maintaining the inter-cluster routing table of each CH. Thus, the total number of messages at this phase is:

$$C(4k(k-1)-1) \quad \ldots (5.3)$$

*Phase* 3: The local broadcasting of the hole information. The number of empty VCs in all the holes is $2WL/d^2 - C$. That is, hole information messages are locally broadcasted in the vicinity of $h$-hop long transmission range.

Almost 8*($h$-1) CHs need to forward each message, except those empty VCs. Then, approximately the total number of messages at this phase is:

$$4h(h-1)(2WL/d^2 - C) \quad \ldots (5.4)$$

*Summation:* by adding formulae 5.2, 5.3, and 5.4 together, we get: $$N - 4k(k-1)C - 4h(h-1)(2WL/d^2 - C) \quad \ldots (5.5)$$

Suppose $k$=$h$, Formula 5.5 can be simplified as:

$$N + 4k(k-1)\,2WL/d^2 \quad \ldots (5.6)$$

From Definition 3, we get $WL=\gamma N$. Then Formula 5.6 can be simplified as Formula 5.7, which is the control complexity:

$$(1+8\gamma k(k-1)/d^2)N \quad \ldots (5.7)$$

In GPSR, to provide all nodes with their neighbors' location, each node periodically transmits a beacon to its neighbors with its own ID and the location. Thus, $N$ messages are needed. So the control complexity is $O(N)$. We set the value of $\gamma$ as same as the simulation in GPSR [5], then $\gamma$= 9000m$^2$ /node, and the transmission range of short radio $r$ is the 802.11 WaveLAN radio, with a normal range of 250m. In our simulation (see Section 5) $d = 400\sqrt{2}$ m. And $k$ has been set as 2 or 3. Then

$$8\gamma k(k-1)/d^2 \le 8*9000*3*(3-1)/(400\sqrt{2})^2 \le 1 \quad \ldots (5.8)$$

So $$(1+8\gamma k(k-1)/d^2)N \le 2N \quad \ldots (5.9)$$

The control complexity of our proposed algorithm approximates that of GPSR. □

## VI. Simulation Results

This section presents simulation results on the routing delay caused by the proposed logical-location-based routing algorithm. The delay is measured by the hop count. Similar to the simulation of GPSR in [5], the mobility of MNs follows the random waypoint model, and the node density is 9000m$^2$ /node. We simulate networks with two size. Table 1 lists the setting of the simulation parameters.

**Table 1. Simulated Parameters**

| Nodes | Region | VCs | Maximal velocity | Pause time | $k/h$ |
|---|---|---|---|---|---|
| 960 | 3600m*2400m | 9*6 | 10m/s | 5s | 2 |
| 3840 | 7200m*4800m | 18*12 | 10m/s | 5s | 3 |

The VCs are formed based on small square regions with fixed side length of 400m. Then, the diameter of VC is $d = 400\sqrt{2}$, the transmission range of long radio is $R = 3/2\, d = 600\sqrt{2}$. The short radio is the 802.11 WaveLAN radio, with transmission range $r$ = 250m. In the simulation, CH is elected based on the ($p$, $t$, $d$)-clustering algorithm in [12] (Here, $d$ denotes the distance from an MN to the center of the cluster where it resides). This clustering algorithm makes the CH to reside close to the VCC, thus, most of time a CH can communicate with all of its eight neighboring CHs, but there are still some situations that a CH can not communicate with one of its neighboring CHs, or a CH can communicate directly with its two-hop neighboring CHs. We have the following definition of *VC distance* between two MNs:

**Definition 5:** Suppose a pair of MNs whose location information is known. If the VCC coordinate of the VC where they reside are $(X_1, Y_1)$, $(X_2, Y_2)$ respectively, then the VC distance between the two MNs is:

$$\left\lfloor \sqrt{(X_1-X_2)^2+(Y_1-Y_2)^2} \Big/ \tfrac{\sqrt{2}}{2}d \right\rfloor$$

Fig.5 shows that the maximum/average/minimum hop count increase with the VC distance in three different situations, when the network size is 3600m*2400m. Fig.5 (a) is the ideal case, where no hole exists in the network, Fig.5 (b) is for the situation with one hole consisting of 3 empty VCs, and Fig.5 (c) is for the situation with one hole consisting of 6 empty VCs. From Fig.5, we can see that the variation of maximum/average/minimum hop count in the three situations is closer to each other. This demonstrates that the proposed algorithm does not cause much delay in handing the holes.

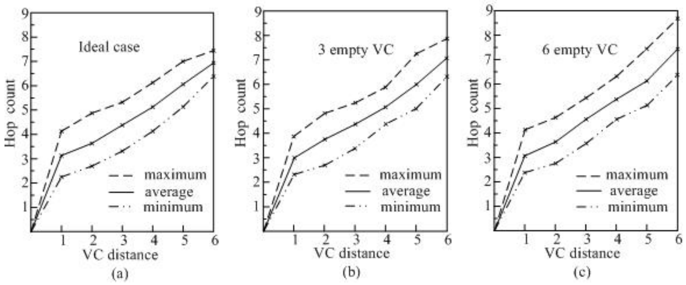


**Fig.5 Network Size: 3600m*2400m**

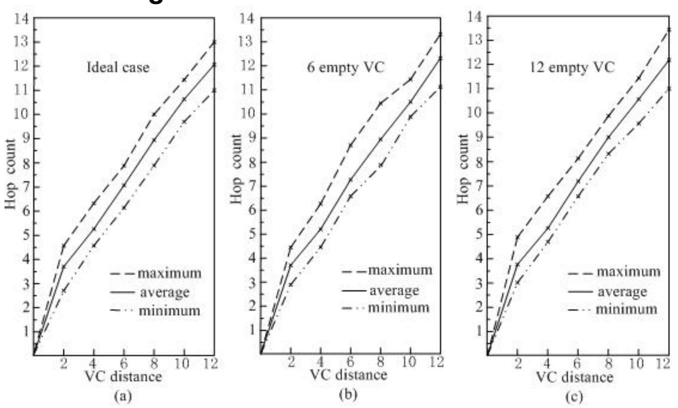


**Fig.6 Network Size: 7200m*4800m**

Fig.6 shows that the maximum/average/minimum hop count increase with the VC distance in three different situations, when the network size is 7200m*4800m. Fig.6 (a) is the ideal case, no holes exist. Fig.6 (b) is for the situation with one hole consisting of 6 empty VCs, and Fig.6 (c) is for the situation with one hole consisting of 12 empty VCs. Fig.6 shows that the variation of maximum/average/minimum hop count in the three situations is also close to each other. This demonstrates that the proposed algorithm does not cause much delay in handing the holes.

Generally speaking, the hop count from source *S* to destnation *D* is calculated by considering four parts: *S*→the CH of *S*→ intermediate CHs→ the CH of *D*→*D*. One or two parts are omitted when the source, or the destination, or both are CHs. Results shown in Fig.5 and Fig.6 demonstrates this general situation. Notice that the variation of the curves in Fig.6 is larger than that in Fig.5 because the increase step of VC distance in the former is twice that in the latter.

In summary, the simulation results show that the proposed logical- location-based routing algorithm can solve the local optimum problem by avoiding the hole in advance. The simulation results in large network size of 7200m*3600m with thousands of MNs also show that the proposed algorithm scales very well when the network size becomes large.

## VII. CONCLUSIONS

This paper introduced a stable logical mesh-based virtual dynamic backbone model. And based on the model a logical-location-based routing algorithm is proposed. The algorithm uses the local topology information for local routing and logical location information for remote routing. Specially, we use the logical location of a mobile node in the sense that the location is actually the identity of the fixed virtual circle region where the mobile node resides. Moreover, a novel hole-shadowing-based forwarding strategy is proposed to avoid local optimum due to holes, which usually occurs in location-based routing algorithms. Performance analysis shows that the proposed algorithm outperforms the GPSR routing algorithm in terms of tolerating the location inaccuracy and communication complexity, with a little larger control complexity. Simulation results show that the proposed algorithm achieves a short routing delay, which is a prerequisite to achieve scalability for large-scale MANETs.

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