Issues in Scalable Clustered Network Architecture for Mobile Ad Hoc Networks

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Abstract

As a large-scale, high-density multi-hop network becomes desirable in many applications, there exists a greater demand for scalable *mobile ad hoc network* (*MANET*) architecture. Due to the increased route length between two end nodes in a multi-hop MANET, the challenge is in the limited *scalability* despite the improved spatial diversity in a large network area. Common to most of existing approaches for a scalable MANET is the *link cluster architecture* (*LCA*), where mobile nodes are logically partitioned into groups, called *clusters*. Clustering algorithms select master nodes and maintain the cluster structure dynamically as nodes move. Routing protocols utilize the underlying cluster structure to maintain routing and location information in an efficient manner. This paper discusses the various issues in scalable clustered network architectures for MANETs. This includes a classification of link-clustered architectures, an overview of clustering algorithms focusing on master selection, and a survey of cluster-based routing protocols.

Keywords: Mobile ad hoc network, scalability, capacity, spatial locality, link cluster architecture, clustering algorithm, cluster-based routing protocol.

1. Introduction

Mobile ad hoc network (MANET) is an infrastructure-less multihop network where each node communicates with other nodes either directly or indirectly through intermediate nodes. Since MANETs are infrastructure-less, self-organizing, rapidly deployable wireless networks, they are highly suitable for applications involving special outdoor events, communications in regions with no wireless infrastructure, emergencies and natural disasters, and military operations. Handling node mobility may be the most critical issue in a MANET, and thus previous research efforts have focused mostly on routing or multicasting protocols that result in consistent performance in the presence of wide range of mobility patterns.

As large-scale, high-density multi-hop networks become more desirable for many applications, a greater demand exists for scalable MANET architecture. However, when the network size increases, routing schemes based on the flat network topology (or flat routing protocols) become infeasible because of high protocol overhead and unreliability/interference caused by broadcasts, which is due to network-wide flooding of routing-related control packets [1, 2]. Recently, a number of studies have addressed this problem. For example, Li *et al*. suggested that a large-scale multihop network is feasible only when most of communication is local so that the broadcasts of routing-related control packets are restricted to the local areas rather than flooded to the entire network [3]. Morris *et al.* considered scaling of MANETs to hundreds of thousands nodes, where control packets are not flooded but directed only to some particular locations where the intended destination is most likely to be located [4]. Grossglauser and Tse also proposed an approach where each node localizes its data transfers by buffering the traffic until the destination node is within its radio range [5]. While the last solution increases delay and requires a large buffer at each node, the first two approaches either require a special facility such as GPS (Global Positioning System) to track nodes' locations or assume communication traffic follows a certain pattern.

Recently, more general approaches for a scalable MANET have been explored in the literature [6-18, 32, 33, 36]. A common aspect to these approaches is that the flat network topology is restructured to produce the *link cluster architecture* (*LCA*), which is one of the promising architectural choices for a scalable MANET [6]. Typically, an entire multi-hop MANET is divided into a number of one- or two-hop networks, called *clusters*, and the clusters are independently controlled and dynamically reconfigured as nodes move. Within each cluster, one node is chosen to perform the function of a *master*[1] and some others to perform the function of *gateways* between clusters. The cluster architecture improves the scalability by reducing the number of mobile nodes participating in some routing algorithm, which in turn significantly reduces the routing-related control overhead. Other advantages are less chances of interference via coordination of data transmissions, and more robustness in the event of node mobility by judicially selecting stable nodes as masters.

This paper presents a survey of routing protocols for clustered architecture in a large-scale MANET, which can be classified into the following two types:

- LCA for Routing Backbone and
- LCA for Information Infrastructure.

The latter type overlays an information infrastructure that supports an efficient means of providing routing information, and the former type constructs a routing backbone which not only maintains routing information but also delivers data packets to intended destinations. Master nodes in a cluster architecture-based protocol collectively maintain routing information of all mobile nodes. For nodes in each cluster, a proactive scheme (distance vector or link state) is quite reasonable because the network diameter of each cluster is usually small and thus the corresponding control overhead is not high. However, for nodes outside of a cluster, each master node uses either one of the following routing principles as in flat routing protocols:

- Proactive update or
- On-demand searching.

The paper is organized as follows: Section 2 presents the classification of cluster architecture-based routing protocols for MANETs based on the abovementioned cluster architectures and routing principles. Sections 3 and 4 describe numerous cluster-based routing protocols with the discussion on cluster type they construct, corresponding control and clustering overheads, and advantages and disadvantages. In particular, Section 3 focuses on routing protocols on LCA for routing backbone and Section 4 on those based on LCA for information infrastructure. Section 5 summarizes all the cluster-based protocols with comparisons and draws conclusions.

[1] Master nodes are alternatively called as cluster heads [9], coordinators [32], core [35], leader [31] or a member of dominating set [10] or a backbone network [11].

2. Classification of Cluster Architecture-based Routing Protocols

Before discussing each protocol in detail, this section provides the classification of cluster-based routing protocols. The classification is based on cluster structures these protocols build and routing methods they employ to find the destination node or the destination node's master. Section 2.1 briefly overviews flat routing protocols proposed for MANETs. Section 2.2 introduces several cluster structures and their characteristics. Section 2.3 introduces routing principles used in cluster-based routing protocols and the overall classification.

2.1 Flat Routing Protocols and Their Scalability

The routing protocols proposed for MANETs are generally categorized as either *table-driven* or *on-demand driven* based on the timing of when the routes are updated. With table-driven routing protocols, each node attempts to maintain consistent, up-to-date routing information to every other node in the network. This is done in response to changes in the network by having each node update its routing table and propagate the updates to its neighboring nodes. Thus, it is *proactive* in the sense that when a packet needs to be forwarded the route is already known and can be immediately used. As is the case for wired networks, the routing table is constructed using either *link-state* or *distance vector* algorithms containing a list of all the destinations, the next hop, and the number of hops to each destination. Many routing protocols including *Destination-Sequenced Distance Vector* (*DSDV*) [19] and *Fisheye State Routing* (*FSR*) protocol [20] belong to this category, and they differ in the number of routing tables manipulated and the methods used to exchange and maintain routing tables.

With on-demand driven routing, routes are discovered only when a source node desires them. *Route discovery* and *route maintenance* are two main procedures: The route discovery process involves sending a route request packet from a source to its neighbor nodes, which then forward the request to their neighbors, and so on until the route request packet reaches the destination node. Once the route is established, some form of route maintenance process maintains the routes in each node's internal data structure. Each node learns the routing paths as time passes not only as a source or an intermediate node but also as an overhearing neighbor node. In contrast to table-driven routing protocols, not all up-to-date routes are maintained at every node. *Dynamic Source Routing* (DSR) [21] and *Ad-Hoc On-Demand Distance Vector* (AODV) [22] are examples of on-demand driven protocols.

Now consider the scalability of these flat routing protocols as network size increases with the number of mobile nodes, *n*. The total effective bandwidth increases as $O(n)$ because more concurrent transmissions can be supported. However, this advantage of spatial reuse is diminished due to the increased path length ($O(n)$) in a larger network area. For this reason, network-wide end-to-end bandwidth remains the same even though network size increases [23, 24]. While this scenario holds for data traffic, this is not true for control traffic caused by the underlying routing protocol. The increased path length causes more chance of route failures and results in higher overhead to maintain the routes. More importantly, in a table-driven routing protocol, the size of routing table grows as function of $O(n)$ as network size increases and the control traffic due to the periodic exchange of the routing tables grows as function of $O(n^2)$ because more number of nodes exchange larger tables. In an on-demand routing protocol such as DSR, a route request packet is broadcast to a larger number of nodes with higher frequency and thus the control traffic is also increased as function of $O(n^2)$.

In addition to the higher protocol overhead mentioned above, a large-scale MANET suffers from unreliable broadcasts. Unlike unicast communication that usually employs *four-way handshake* (Request-to-Send, Clear-to-send, Data, and Acknowledgement packets) [25] to improve link-level reliability, broadcasts are inherently unreliable in wireless ad hoc networks. A large-scale MANET aggravates the problem because such broadcasts are performed in a series, one after the other [1]. Redundant broadcasts and contention/collisions among the broadcasts [26] significantly increase the control overhead in a large-scale MANET.

2.2 Cluster Architectures

Cluster architecture is a scalable and efficient solution to the abovementioned problems by providing a hierarchical routing among mobile nodes. Fig. 1 shows different cluster architectures with different level of cluster overlapping and different responsibilities imposed on master nodes. As introduced in Section 1, they can be broadly categorized into two types based on how the master nodes are utilized: *LCA for Routing Backbone* and *LCA for Information Infrastructure*. A straightforward difference between the two types is that the former imposes more responsibility on master nodes but the latter needs to provide an additional mechanism for routing. An important design issue in the information infrastructure approach is to select a set of master nodes that gather and scatter routing information with minimal overhead. On the other hand, in the routing backbone approach, maintaining master-to-master connections and high-level topology among the masters are more important issues in order to deliver data packets efficiently.

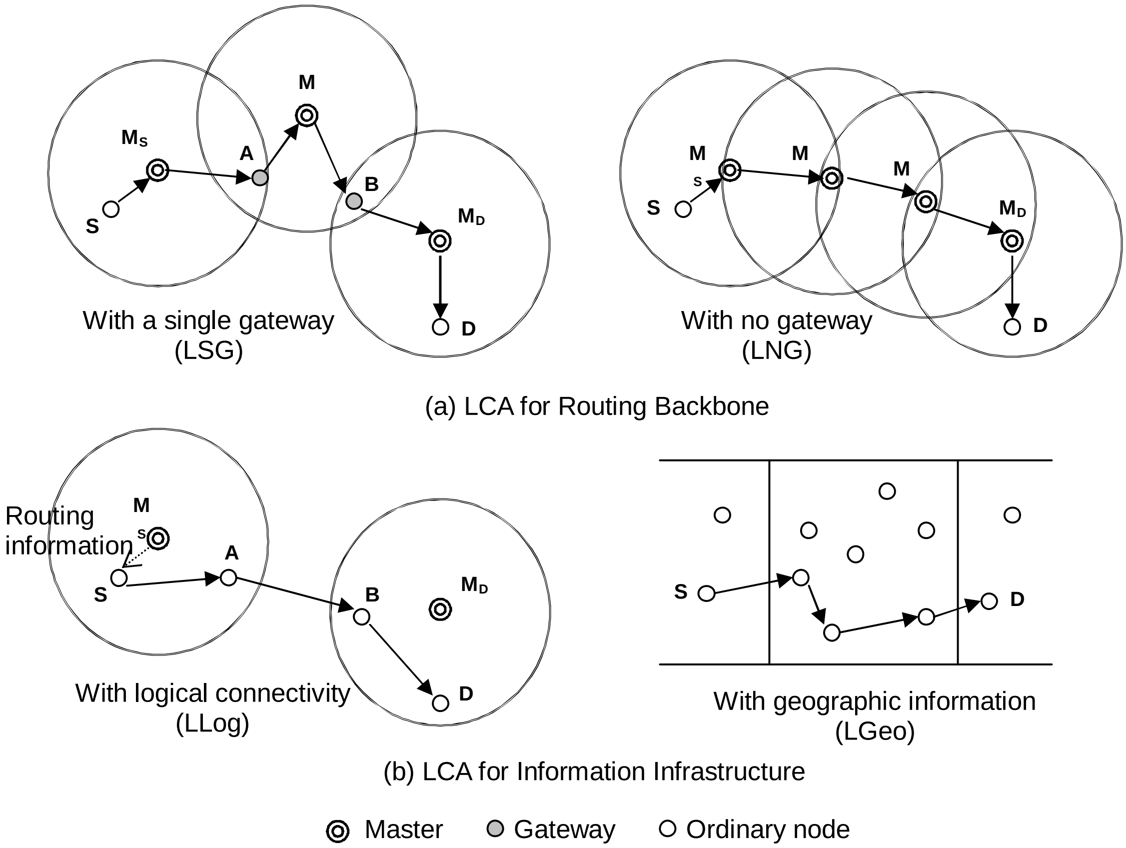


Fig. 1. LCA classification.

Fig. 1(a) shows examples of routing backbones through which data packets are routed. Depending on the number of gateways between two masters, they are called as *LCA for routing backbone with a single gateway* (*LSG*) and *with no gateway* (*LNG*), respectively. In LNG, master nodes perform the functions of gateways, and thus, intermediate nodes in a routing path consist only of masters. Span [32], NTDR networking [33], and GAF [34] are example protocols that construct LNG. CGSR [27], HSR [28], CBRP [30], ARC [31], DSCR [27] and LANMAR [29] construct LSG. Note that CBRP and ARC also allow two neighboring masters to contact directly or indirectly via a pair of gateways. This is to avoid frequent changes in masters and prevent network partitioning as will be discussed in Section 3.1.

Approaches for constructing routing backbones shown in Fig. 1(a) impose high demand on channel bandwidth and require node stability on the backbone nodes to prevent bottlenecks as well as a single point of failure. In addition, they may result in suboptimal routing paths because every intermediate node must be either a master or a gateway. Therefore, an alternative solution is to construct a virtual infrastructure that serves only as container for routing information as in Fig. 1(b). Routing is carried out based on the flat routing principle without going through masters but route searching is more localized based on the virtual information infrastructure [11]. CEDAR [35], ZRP [36], ZHLS [37] and GLS [38] routing protocols fall into this category. It is noted that the last two protocols use geographic location information obtained via GPS to define clusters, which we refer to as *LGeo* (*LCA for information infrastructure with geographic information*). Once a destination's physical location is obtained, a more efficient routing scheme can be employed. Other protocols define clusters based on logical connectivity, which we refer to as *LLog* (*LCA for information infrastructure with logical connectivity*). DDCH [11] and MMDF [13] are also efficient clustering algorithms but not complete routing protocols, which we also include in our discussion.

2.3 Cluster-based Routing Protocols

The main idea behind constructing an LCA is to reduce the routing-related control overhead involved with searching for the destination node in a large network. Each master node can easily maintain the location information of ordinary nodes in its cluster using local communications. However, in order to obtain information of a destination node D in a remote cluster, each master has to perform the following tasks: Identify the cluster where the destination node D or its master node M_D is located, and forward data packets toward M_D and let it deliver the packets to D. Therefore, the node-master association (D, M_D) for all nodes must be maintained. A cluster-based routing protocol updates the association table based on either

- proactive update of the association of all nodes or
- on-demand searching for M_D corresponding to D

among master nodes over the underlying cluster structure.

Proactive approaches can provide a faster data delivery but a large table containing associations for all mobile nodes needs to be periodically propagated. Notice, however, that the corresponding overhead is far less than that of maintaining link status or distance vector to all nodes because node-master association changes less frequently than wireless link status. Moreover, by applying a more stable cluster structuring algorithm, which we will discuss in Section 3.1, the update period can be greatly reduced. On the other hand, for on-demand approaches, the master node M_D is searched based on typical *route discovery procedure* as used in on-demand flat routing protocol such as DSR [21] or AODV [22]. The underlying cluster structure is used to relay the route request packet in order to avoid the overhead of network-wide search. Table 1 summarizes cluster-based routing protocols and their characteristics.

Table 1: Cluster-based protocols and their cluster architectures.

Cluster architecture	Routing principle for nodes outside of a cluster	
	Proactive update	On-demand searching
LCA for routing backbone	LSG with master-to-gateway routing (Section 3.2): CGSR (Cluster Gateway Switching Routing) [27] HSR (Hierarchical State Routing) [28] LSG with flat routing (Section 3.2): DSCR (Destination Sequenced Clustering Routing) [27] LANMAR (Landmark Ad Hoc Routing) [29]	LSG (no or two gateways are also allowed) (Section 3.2): CBRP (Cluster Based Routing Protocol) [30] ARC (Adaptive Routing using Clusters) [31] LNG with master-to-master routing (Section 3.3): SPAN [32] NTDR (Near-Term Digital Radio) [33] GAF (Geographic Adaptive Fidelity) [34]
LCA for information infrastructure		LLog (Section 4.2): CEDAR (Core-Extraction Distributed Ad Hoc Routing) [35] ZRP (Zone Routing Protocol) [36] LGeo (Section 4.3): ZHLS (Zone-based Hierarchical Link State) [37] GLS (Grid Location Service) [38]

3. LCA for Routing Backbone

One important design problem in constructing an LCA for routing backbone is to select master nodes so that they can form an efficient routing infrastructure. Section 3.1 discusses the master selection and cluster maintenance algorithms for LSG and LNG in a MANET. Sections 3.2 and 3.3 discuss the LSG- and LNG-based routing protocols, respectively.

3.1 Clustering Algorithms

Designing a clustering algorithm is not trivial due to the following reasons. First, electing a master node among a set of directly connected nodes is not straightforward because each candidate has a different set of nodes depending on the spatial location and the radio transmission range. Second, a clustering algorithm must be a distributed algorithm and be able to resolve conflicts when multiple mutually exclusive candidates compete to become a master. Third, the clustering algorithm must be able to dynamically reconfigure the cluster structure when either some nodes move or some masters need to be replaced due to overloading. Finally, another difficulty is that, in the presence of mobility, it must preserve its cluster structure as much as possible and reduces the communication overhead to reconstruct clusters [7]. Below we will discuss the cluster construction problem involving the first two issues, and then explain the cluster maintenance algorithm that must deal with the last two issues.

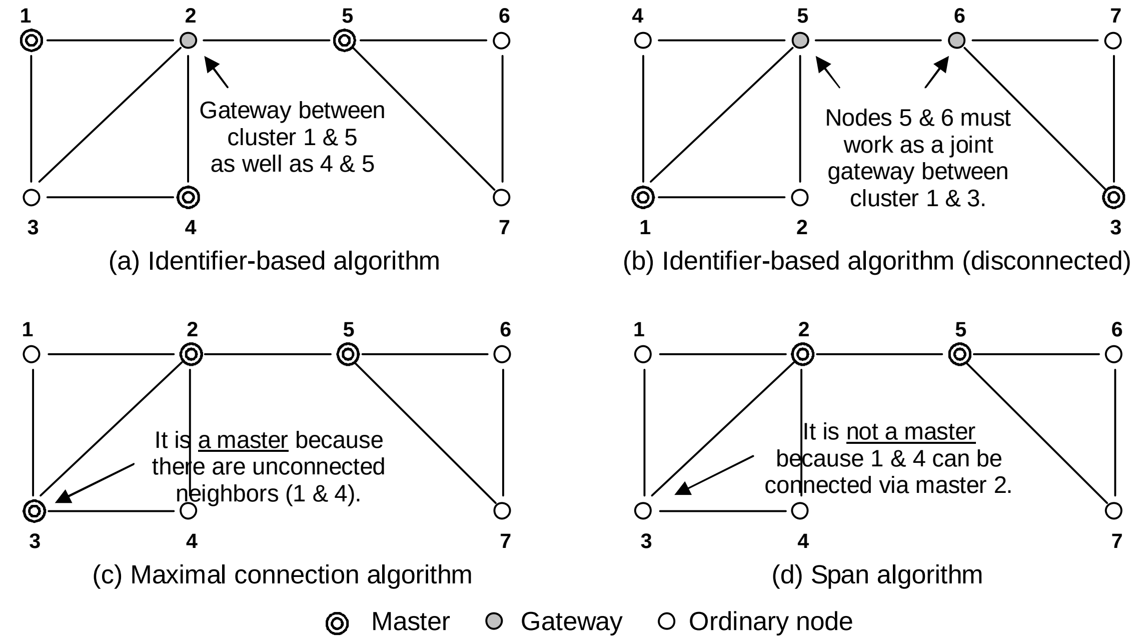


Fig. 2. Master selection algorithms.

Master Selection Algorithms for LSG

There are various clustering algorithms used to construct a LSG. In the *identifier-based algorithm* [6], a node elects itself as a master if it has the lowest-numbered identifier in its uncovered neighbors, where any node that has not yet elected its master is said to be uncovered. Fig. 2(a) shows the process of master selection based on this algorithm. Nodes 1 and 4 elect themselves as masters and nodes 2 and 3 are covered by those masters. Among uncovered nodes (nodes 5, 6 and 7), node 5 elect itself as a master because it has the lowest identifier. By definition, a master node cannot have another master as a neighboring node and thus, this algorithm produces an single-gateway structure. The *connectivity-based algorithm* [6] uses the node connectivity instead of node identifier to determine a master because it potentially provides a cluster structure with less number of masters. (When a tie occurs, node identifier is used to resolve the conflict.)

In the *randomized clustering algorithm* [33], a node elects itself as a master if it does not find any masters within its communication range. Since multiple candidates may compete to become a master, conflicts are resolved by a random delay. That is, when a node detects no neighboring master nodes, it first waits for a randomly selected time. If it still detects no master nodes after the delay, it now becomes the master and immediately announces this information to its neighbors. This algorithm is logically the same as the identifier-based algorithm when the random wait time is translated to the node identifier. The *adaptive clustering algorithm* proposed in [7] forms disjoint clusters, where each cluster is assigned a different communication channel from those in neighboring clusters. Without this assumption, the algorithm is equivalent to identifier-based clustering algorithm and results in a single-gateway network.

Identifier- or connectivity-based algorithms are the basic clustering algorithms used in most of cluster-based routing protocols. In order to implement these algorithms, each node periodically broadcasts its identifier or connectivity information to its neighbors and elects a master which has the lowest identifier or the highest connectivity. However, it is important to note that these clustering algorithms may not form a connected cluster structure. It happens when the overlapping area between two adjacent clusters does not contain any single mobile node and thus there is no node assuming the task of a gateway between two clusters. For example, Fig. 2(b) shows the same ad hoc network as in Fig. 2(a) but with different assignments of node identifiers. Identifier-based clustering algorithm selects nodes 1 and 3 as masters but there is not a single node which is included in both clusters.

CBRP [30] and ARC [31] protocols take this problem into account by allowing a pair of gateways between two masters. In Fig. 2(b), nodes 5 and 6 should work as gateways between two clusters. However, it takes a larger data exchange between neighboring nodes. Periodic broadcasts by each node are piggybacked with information on master nodes that the node can contact directly or indirectly via another node. Thus, each master is able to find out other neighboring masters that are 2 hops as well as 3 hops away. A pair of gateways or a *joint gateway* [31] can thus be found for two nearby masters that are separated by three hops.

Cluster Maintenance Algorithms for LSG

Now, we consider the cluster maintenance procedure. Mobility of ordinary nodes can be simply handled by changing its master node accordingly. Mobility of a master node is a more difficult problem not only because a new master node must be elected but also because it may affect the entire cluster structure of the network. The identifier-based clustering is more stable than the connectivity-based clustering because connectivity changes frequently as nodes move. In [7], the authors measured the stability of cluster architecture by counting how many nodes migrate from one cluster to another and demonstrated the importance of the stability factor by showing that it directly affects the general network performance.

There are some mechanisms to make the cluster structure more stable. *Least Cluster Change* (*LCC*) clustering algorithm is the most common denominator, which is used in CGSR [27], CBRP [30], ARC [31], and DSCR [27]. The two LCC rules are as follows:

(i) When an ordinary node contacts another master, no change in mastership occurs without re-evaluating the basic master selection rule such as lowest-id or highest-connectivity clustering algorithm.

(ii) When two masters contact each other, one gives up its mastership based on the basic rule among the two but not among all possible candidates. Some nodes in the loser's cluster should re-elect a new master since they are not within the transmission range of the winning master.

However, the problem the second LCC rule is that it can cause a rippling effect across the network. CBRP [30] modifies the rule a step further to propose the "*contention rule*" to reduce the frequency of changes in mastership. Unlike the second LCC rule stated above, two masters are allowed to contact each other for less than the predefined contention period. The contention rule is effective when two masters contact temporarily and are separated in a short period of time. ARC protocol [31] adopts the "*revocation rule*" replacing the second LCC rule: When two masters contact with each other, one master becomes an ordinary node only when its cluster becomes a subset of the other master's cluster. In other words, CBRP and ARC temporarily allow a cluster structure with no gateway.

However, a highly stable structure may easily overload the master nodes. This may produce many undesirable problems because every mobile node is inherently identical in its capability as well as its responsibility in a MANET. Thus, it is necessary to change the master nodes periodically in order to prevent overloading and to ensure fairness.

Master Selection Algorithms for LNG

The *maximal connection algorithm* [10] shown in Fig. 2(c) is the most straightforward no-gateway algorithm. A node elects itself as a master if there are two neighbors that are not directly connected. With this clustering algorithm, master nodes collectively provide a routing backbone that always guarantees the shortest path. In other words, intermediate nodes of the shortest path between any two nodes are all master nodes. To see this, consider an intermediate node (for example, node 5 in Fig. 2(c)) along a shortest route between nodes 1 and 6 (route 1-2-5-6). Node 5 relays packets between the proceeding (node 2) and the succeeding node (node 6) along the shortest path but, since this node is a part of a shortest route, these two nodes are not directly connected. Therefore, by definition, the intermediate node (node 5) must be a master node because there are two unconnected neighbors.

The *Span algorithm* [32] is a similar scheme but produces less number of master nodes. To select the master nodes, the Span protocol employs a distributed *master eligibility rule* where each node independently checks if it should become a master or not. The rule is *if two of its neighbors cannot reach each other either directly or via one or two masters, it should become a master* [32]. In Fig. 2(d), unlike the maximal connection algorithm, node 3 is not a master node because two of its neighbors, nodes 1 and 4, can be connected via a master node 2. A randomized backoff delay is used to resolve contention. By definition, for each pair of nodes that are two hops away, they are directly connected or there is a two-hop or three-hop route where all intermediate nodes are masters. In other words, master nodes connect any two nodes in the network providing the routing backbone. Therefore, the Span algorithm produces a no-gateway network, even though the paths are not always the shortest.

Master overloading is also a problem in LNG. In the Span algorithm, a master node periodically checks if it should withdraw as a master and gives other neighbor nodes a chance to become a master. Ordinary nodes also periodically determine if they should become a master or not based on the master eligibility rule stated above. Table 2 summarizes the clustering algorithms for LSG and LNG.

Table 2: Clustering algorithms for LCA for routing backbone.

CBR	Protocol	Clustering algorithm	Comment
Single gateway	CGSR [27]	Basic + LCC algorithm	"Basic" means the clustering algorithm based on the lowest identifier or the highest connectivity.
	HSR [28]	Basic algorithm	
	DSCR [27]	Basic + LCC algorithm	
	LANMAR [29]	None	Group mobility is assumed so that relative relationship among mobile nodes in a group doesn't change over time and it results in a natural clustering.
	CBRP [30]	Basic + LCC + Contention rule	A pair of gateways is allowed between two clusters.
	ARC [31]	Basic + LCC + Revocation rule	A pair of gateways is allowed between two clusters.
No gateway	NTDR [32]	None	It is assumed that nodes are clustered around a number of geographic locations and they naturally form clusters.
	SPAN [33]	Span algorithm	Master eligibility rule is defined.
	GAF [34]	None	A network area is geographically partitioned into grids and each node can easily associate it with the corresponding cluster.

3.2 LSG-based Routing Protocols

For cluster-based routing protocols, maintaining node-master association (D, M_D) of all mobile nodes in a MANET is the key issue. Routes to local nodes in each cluster are usually updated using a proactive algorithm, i.e., each node broadcasts its link state to all nodes within its cluster. Since they share the same master, their node-master associations are automatically updated. However, node-master association of remote nodes is maintained either proactively or reactively. This section discusses six cluster-based routing protocols, four proactive (CGSR, HSR, DSCR and LANMAR) and two on-demand protocols (CBRP and ARC). Note that, even though these protocols are all based on single-gateway cluster structure, two protocols (DSCR and LANMAR) use flat routing scheme rather than conventional master-to-gateway routing. Nevertheless, we categorize them as LSG protocols because data packets are routed via ordinary nodes toward M_D, thus one master node plays an important role in routing.

CGSR and HSR: Proactive Protocol with Conventional Master-to-Gateway Routing

In CGSR (*Cluster Gateway Switching Routing*) [27], each master node maintains the distance and vector to all other masters based on the DSDV routing principle. The next hop node to each of the neighboring maters should be a gateway shared by the two clusters and thus CGSR offers a hierarchical master-to-gateway routing path. Each node keeps a "*cluster member table*" where the node-master associations of all mobile nodes in the network are stored, and this information is broadcast periodically to other nodes. Upon receiving a packet, a node consults its cluster member table and routing table to determine the nearest master along the route to the destination. Next, the node checks its routing table to determine the particular node that can be used to reach the selected master. It then transmits the packet to this node. Fig. 3(a) shows an example of the CGSR routing protocol between *S* and *D*.

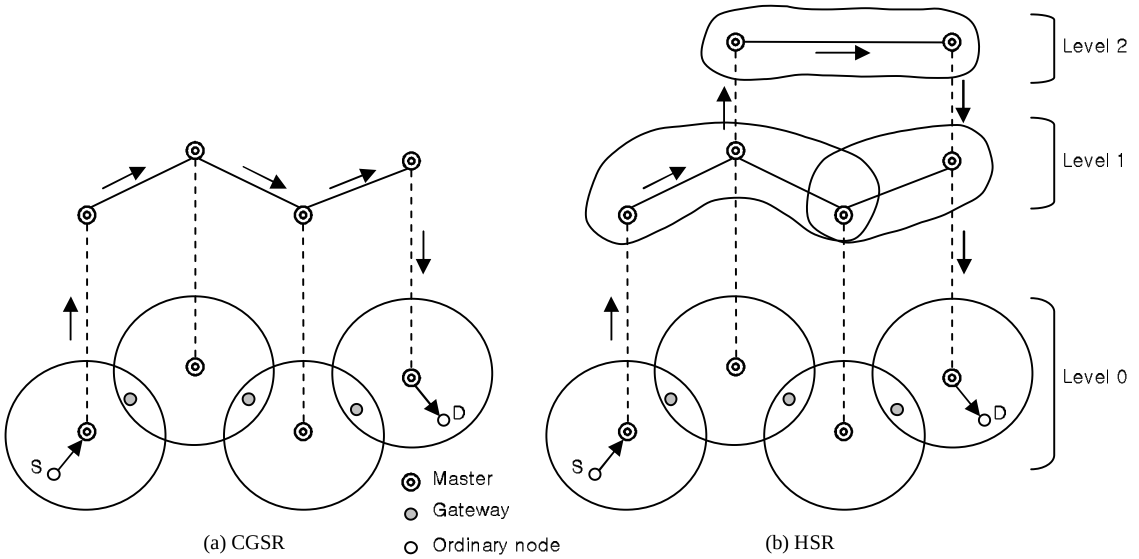


Fig. 3. CGSR [27] and HSR [28] protocols.
(Proactive maintenance of node-master associations and conventional master-gateway routing paths)

The *HSR (Hierarchical State Routing)* protocol [28] combines dynamic, distributed multi-level hierarchical clustering with an efficient location management. It maintains a hierarchical topology, where elected masters at the lowest level become ordinary nodes of the next higher level. The ordinary nodes of a physical cluster (in the lowest hierarchy) broadcast their link information to each other. The master summarizes its cluster's information and sends it to neighboring masters via gateway as it is in CGSR. Fig. 3(b) shows an example of the HSR routing protocol with three levels of hierarchy.

In HSR, a new address for each node, *hierarchical ID* (*HID*), is defined as the sequence of MAC addresses of the nodes on the path from the top hierarchy to the node itself. This hierarchical address is sufficient to deliver a packet to its destination by simply looking at the HID. However, the drawback of HSR also comes from using HID, which requires a longer address and frequent updates of the cluster hierarchy and the hierarchical addresses as nodes move. In a logical sense, this is exactly the same as the "cluster member table" defined in CGSR. However, in case of HSR, the main difference is that the corresponding overhead depends on mobility, and it may become zero when nodes do not move and there is no HID change.

DSCR and LANMAR: Proactive Protocols with Flat Routing toward M_D

DSCR (*Destination Sequenced Clustered Routing*) [27] is similar to CGSR and HSR in that each node maintains the distance and vector to all masters and has complete information on (D, M_D) association of all mobile nodes. The main difference is that DSCR forwards the data packets to the next hop node, which is not necessarily a master or a gateway. In fact, the concept of gateway is not defined in DSCR and data packets are delivered based on a flat routing scheme. A clear advantage of the DSCR protocol is that the route acquisition time is very small and the routing path is usually the shortest one because it does not need to go through other masters or gateways except the destination's master. Fig. 4 shows an example of the DSCR routing protocol.

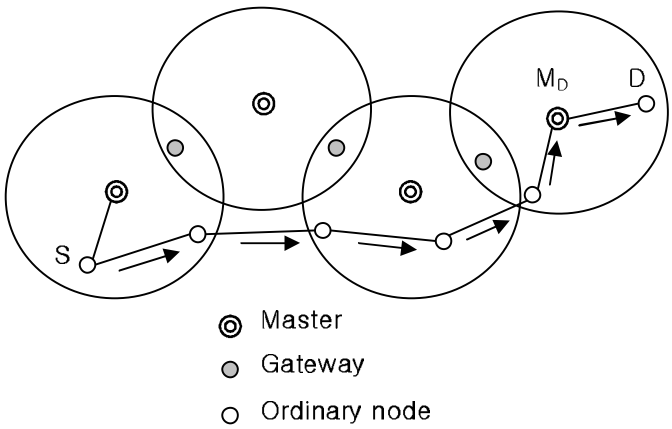


Fig. 4. DSCR [27] and LANMAR [29] protocols.
(Proactive maintenance of node-master associations and flat routing scheme used to deliver packets toward M_D)

In *LANMAR (Landmark Ad Hoc Routing)* [29], nodes move as inherent groups and there is a master node, called a "*landmark,*" in each group. As in DSCR, each node periodically exchanges topology information with its immediate neighbors based on FSR routing principle [20] and exchanges distance vector table to all masters. But unlike DSCR, node-master associations do not need to be updated because they are known to all the participating nodes. Advantages of LANMAR are small route acquisition time and the shortest routing path. As in DSCR, a routing path does not go through any master nodes, including the destination's master node, M_D. When the packet reaches near the destination cluster, any node who receives the packet may know the destination as one of its neighbors and directly delivers the packet rather than forwarding it to M_D. Fig. 4 shows an example of the LANMAR routing protocol, which is conceptually the same as DSCR.

CBRP and ARC: On-Demand Protocols with Conventional Master-to-Gateway Routing (Allowing No, Single or Joint Gateways)

In *CBRP* (*Cluster Based Routing Protocol*) [30] and *ARC* (*Adaptive Routing using Clusters*) [31], each node periodically broadcasts its link state to its neighbors as in CGSR and HSR with additional information on neighboring masters which it learns from its neighbors (*neighbor* or *node table*). Therefore, a master is aware of all the ordinary nodes in its cluster and all neighboring masters that are two hops and three hops away (*cluster adjacency* or *cluster master table*), and thus, they support a pair of gateways between two clusters. For each neighboring cluster, the table has entry that contains the gateway through which the cluster can be reached and the master of the cluster.

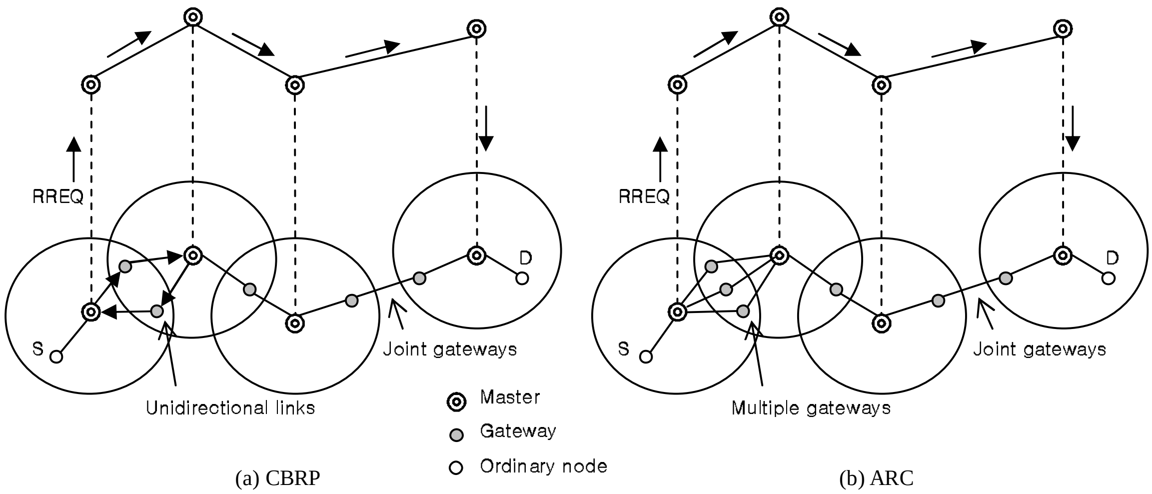


Fig. 5. CBRP [30] and ARC [31] protocols.
(On-demand searching for node-master association and
conventional master-gateway routing paths allowing a pair of gateways between clusters)

For (D, M_D) association, CBRP and ARC take an on-demand approach (unlike CGSR and HSR). When a source, *S*, has to send data to a destination, *D*, route request packets are flooded only to the neighboring masters. On receiving the request, a master checks to see if *D* is in its cluster. If so, then the request is sent directly to the destination; otherwise, the request is sent to all its adjacent masters. When the route request reaches *D*, it replies back to *S* via the intermediate masters and gateways. Fig. 5(a) and 5(b) show examples of the CBRP and ARC routing protocol, respectively.

While the route reply packet goes through the master-to-gateway routing path, intermediate masters can calculate an optimized hop-by-hop route while forwarding the reply packet. Thus, data packets may not follow the master-to-gateway routing path and offers the shortest path [30]. Fig. 5(a) shows an example of the CBRP routing protocol. A unique feature to the CBRP is that this protocol takes asymmetric links into account, which makes use of unidirectional links and, thus, can significantly reduce network partitions and improve routing performance.

Two new ideas in ARC are: (i) Master revocation rule to preserve the existing cluster structure as longer as possible and thus reduce the clustering overhead (see Section 3.1), and (ii) multiple gateways between clusters for more stable connections. While data packets are forwarded through the hierarchical master-to-gateway routing path, packet header in each data packet contains a source route in the form of master-to-master connections. The benefit of this is that each intermediate master can adaptively choose a gateway when it forwards the data packet to the next hop master, and thus provides better packet delivery capability.

3.3 LNG-based Routing Protocols (On-demand Protocols with Master-to-Master Routing)

One of main benefits of building a no-gateway structure is energy conservation in addition to the routing efficiency. Each node can save energy by switching its mode of operation into *sleep mode* when it has no data to send or receive. *Span* [32] and *GAF* (*Geographic Adaptive Fidelity*) [34] adopt this approach. In *NTDR* (*Near-Term Digital Radio*) [33], each node saves power by reducing its transmission power just enough to reach local nodes while a master should have a large transmission power to reach nodes in remote clusters. In either case, LCA is essentially used, where a master node coordinates the communication on behalf of ordinary nodes in its cluster.

One clear difference between Span and NTDR is the power model they assume. The cluster architecture in Fig. 6(a) is based on symmetric power model as used in the Span protocol, where master nodes have the same radio power and thus the same transmission range as ordinary nodes. On the other hand, Fig. 6(b) shows the asymmetric power model used in the NTDR protocol, where master nodes have longer transmission range. While Span uses a distributed clustering algorithm discussed in Section 3.1, NTDR does not use any specific clustering algorithm because it is assumed that nodes are naturally clustered in a special environment such as a military setting. On-demand routing principle is used in Span and NTDR, and route request packets and data packets follow master-to-master routing path.

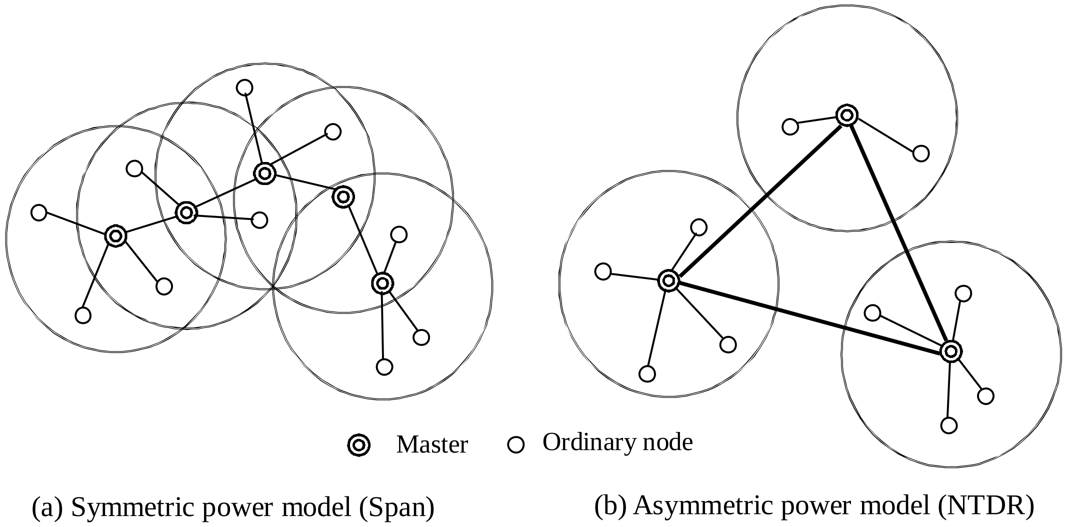


Fig. 6. LNG architecture with different power models.

Routing and energy efficient operation in GAF protocol [34] are similar to Span but the clustering algorithm is fundamentally different. In GAF, each node uses location information based on GPS to associate itself with a "*virtual grid*" so that the entire area is divided into several square grids, and the node with the highest residual energy within each grid becomes the master of the grid. Other nodes in the same grid can be regarded as redundant with respect to forwarding packets, and thus they can be safely put to sleep without sacrificing the "*routing fidelity*" (or routing efficiency).

4. Cluster Architecture for Information Infrastructures

For a large network with many nodes and frequent topology changes, mobility and location management of all mobile nodes pose a high demand of network traffic. The main objective of an LCA for information infrastructure is to select a set of master nodes, which possess routing information of all nodes, so that every ordinary node can reach at least one master within a certain bounded number of hops, e.g., *k* hops. Searching for the destination node's location and the corresponding routing path is localized within a *k*-hop cluster rather than an expensive network-wide search. As discussed in Section 2.2, the cluster structure is based either on logical connectivity (LLog) or geographic information (LGeo). Section 4.1 discusses the master selection algorithms that use these types of LCAs. Section 4.2 and 4.3 discuss LLog- and LGeo-based routing protocols, respectively.

4.1 Clustering Algorithms

The clustering algorithms for TLCA for information infrastructure turns out to be the *minimum set covering* (*MSC*) problem, or called a *minimum dominating set* (*MDS*) problem over a graph representing the ad hoc network. It finds a smallest number of masters such that every node in the network is "covered" within k hops [1, 11, 13, 35]. The MSC or MDS problem is a well-known NP-hard problem [1, 11, 13]. A number of heuristic clustering algorithms have been proposed to select master nodes that approximate a MDS without resorting to global computation. Note that the basic idea of the heuristics is to select lowest-id or highest-connectivity node as discussed in Section 3.1 with the competition extended to k-hop neighbors rather than just direct (one-hop) neighbors.

The *CEDAR* (*Core Extraction Distributed Ad Hoc Routing*) protocol [35] is a connectivity-based algorithm with $k = 1$. In order to provide stability to the master selection algorithm, it gives preference to master nodes already present in its neighbors. Among those master nodes, the one that has more nodes in its cluster is given a higher priority. *DDCH* (*Distributed Database Coverage Heuristic*) [11] is another connectivity-based master selection algorithm for the MSC problem: (i) A link state algorithm is employed with the range of link update limited to k hops. (ii) A node is either a master or an ordinary node. An ordinary node can be in one of three states such as *normal*, *panic* and *samaritan*. A node enters the panic state if there is no master within k-hop cluster. It sends and receives state packets within $2k$ hops. If it has the maximum number of panic nodes within its k-hop cluster, it becomes a master node.

MMDF (*Max-Min D-Cluster Formation*) [13] provides another heuristic algorithm for the same MSC problem in the context of ad hoc networks. Unlike CEDAR and DDCH, it is an identifier-based algorithm also extended to k-hop cluster. While identifier-based algorithms are more stable than connectivity-based algorithms (see Section 3.1), they may have a balance problem because every ordinary node in the overlapping area of two nearby clusters selects the higher-id master. Since the overlapping can be quite large in a k-hop cluster structure, cluster sizes tend to be very different and unbalanced. MMDF addresses this problem by using two k rounds of information exchange (*floodmax* and *floodmin*). During the first k rounds, each node selects the highest-id node in each node's k-hop cluster and then, during the second k rounds, it selects the smallest-id node among the survivals in the first *k* rounds. One of the features of the MMDF heuristic is that it tends to re-elect existing masters even when the network configuration changes, and also, there is a tendency to evenly distribute the mobile nodes among the masters, and evenly distribute the responsibility of acting as masters among all nodes.

The clustering approach of *ZRP* (*Zone Routing Protocol*) [36] is unique in that every node is regarded as a master. Each node defines its own *k*-hop cluster and maintains a set of "*border*" nodes as gateways to neighboring clusters. Thus, it does not require a specific master selection algorithm.

In *ZHLS* (*Zone-based Hierarchical Link State*) [37] and *GLS* (*Grid Location Service*) [38], constructing a cluster structure is straightforward based on GPS-like location facility: The network area is geographically partitioned into clusters (*grids*) and each node can easily associate it with the corresponding cluster based on its physical coordinates. In ZHLS, there are no masters but gateways are defined as the ones that have links to neighboring grids. Note that a gateway in this case is included in just one cluster. While exchanging link state information between neighbors, each node recognizes itself as a gateway and it uses the stored routing information when relaying packets to neighboring grids.

In GLS [38], the grid structure has amore than one level hierarchy as in the HSR protocol discussed in Section 3.2. For example, four small sized grids are combined to become a higher-level grid. Each node is located exactly one grid of each size and one master for each of the grid maintains the location information of the node. This means master nodes for a node are relatively dense near the node but sparse further away from the node. A unique feature to GLS is that there is a set of master nodes for each ordinary node, determined by "*consistent hashing*," but the set is totally different from node to node. The rule to select the master of node *D* is: *A node with the least identifier greater than D's identifier among the candidates becomes a master of D, where id space is considered to be circular*. In short, for a given id and a set of candidates, the master node can be deterministically determined. A set of masters for a destination node is used when searching for the location of the node, which we will explain in detail later in Section 4.3. Table 3 summarizes clustering algorithms used in LLog and LGeo.

Table 3: Clustering algorithms for LCA for information infrastructure (*k*-hop clustering).

LCA	Protocol	Cluster structure	Clustering algorithm
LLog	CEDAR [35]	No gateways	Connectivity-based algorithm with k=1. Preference is given to a master which has a larger number of ordinary nodes in its cluster.
	ZRP [36]	Every node is a master.	Every node maintains neighbors within its k-hop cluster and "border" nodes as gateways.
LGeo	ZHLS [37]	No masters Multiple gateways between clusters	Gateways links to neighboring grids and maintain information of the nodes within its grid.
	GLS [38]	Every node has a different set of masters (location servers).	Grid hierarchy is formed where each node is located exactly one grid of each size.

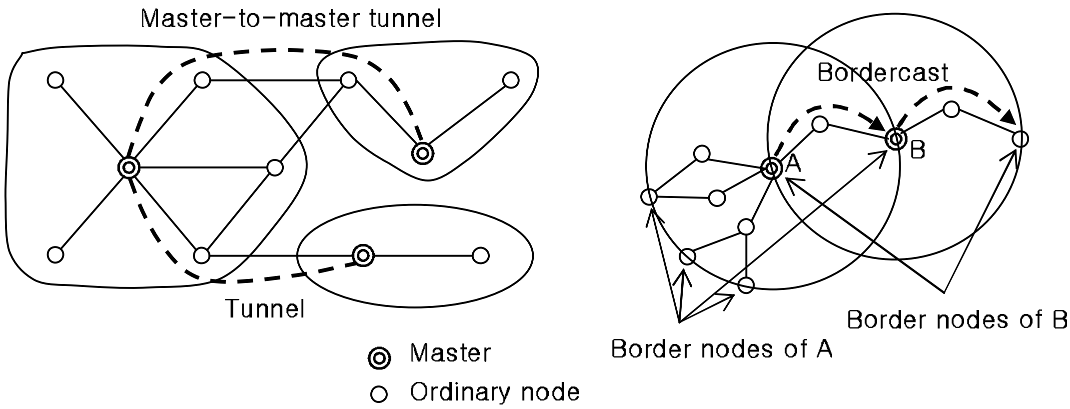
4.2 LLog-based Routing Protocols

As discussed previously in Section 3, maintaining node-master association (D, M_D) of all nodes is the key design issue in a large-scale MANET. In this section, we discuss two routing protocols (CEDAR and ZRP) that utilize cluster architecture as information infrastructure. They employ on-demand routing principle when searching for the location of a destination node.

CEDAR (Core Extraction Distributed Ad Hoc Routing) Protocol [35]

CEDAR has three components: Master selection (*core extraction*), link state propagation, and route computation. Master nodes are dynamically selected using a connectivity-based algorithm discussed in the last section. When S wants to send the packet to D, it informs its master M_S. Then, M_S finds the path to M_D using DSR-like on-demand probing. Two unique features in CEDAR are QoS routing and "*core broadcast*" mechanism. In CEDAR, each node can request a communication path to D with bandwidth requirement. In order to support this, stable high-bandwidth links are advertised further away while relatively unstable low-bandwidth links are known only to its local neighbors.

Core broadcast mechanism is used to discover D or M_D and to propagate link state information of stable links. Since broadcast is inherently unreliable in a wireless environment (see Section 2.1), CEDAR maintains an explicit tunnel between two neighboring master nodes. When a master receives a "core broadcast" message, the master uses the tunnels to unicast the message to all its nearby master nodes. A more recent work combines CEDAR with DSR and AODV to propose *DSRCEDAR* and *AODVCEDAR* [1]. Fig. 7(a) shows the CEDAR protocol with three clusters and master-to-master tunnels.



(a) CEDAR (b) ZRP

Fig. 7. CEDAR [35] and ZRP [36] protocols.

ZRP (Zone Routing Protocol) [36]

In ZRP, each node has a predefined *zone* (*k*-hop cluster) centered at itself in terms of a number of hops. It consists of three components: Within the zone, proactive *IARP* (*intra-zone routing protocol*) is used to maintain routing information. IARP can be any link state or distance vector algorithm. For nodes outside of the zone, reactive *IERP (inter-zone routing protocol)* is performed. IERP uses the conventional route request packets to discover a route. It is broadcast via the nodes on the border of the zone (called "*border*" nodes), and such a route request broadcast is called *BRP* (*Bordercast Resolution Protocol*). Fig. 7(b) shows ZRP with $k = 2$.

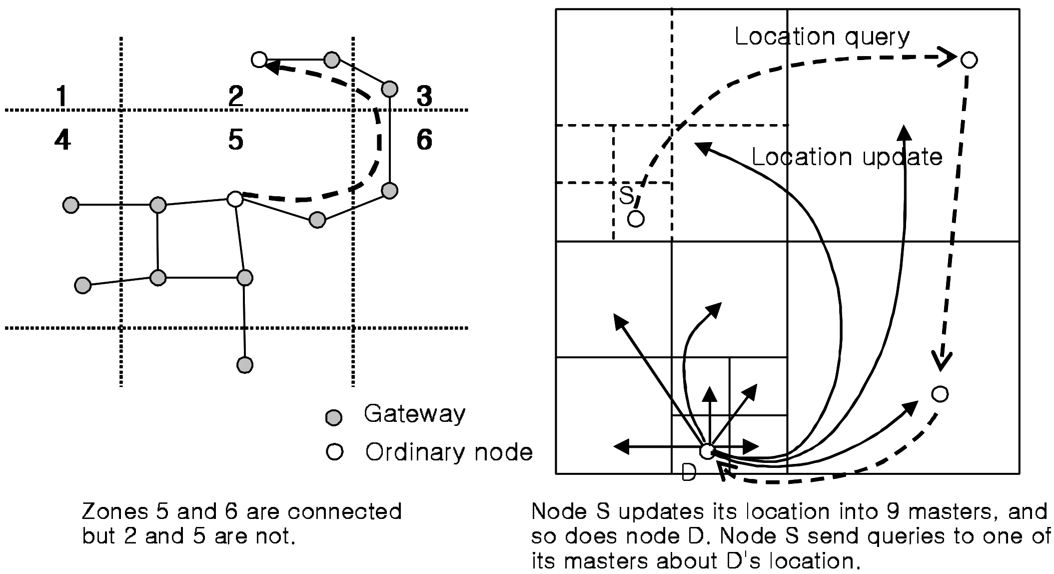
4.3 LGeo-based Routing Protocols

This section discusses ZHLS and GLS where cluster structure is simply given based on physical locations obtained via GPS. Routing principle in ZHLS is on-demand searching for the destination cluster. (Note that it does not search for M_D since masters are not defined in ZHLS.) In GLS, location information of a node is distributed to a number of masters and the routing principle is hybrid of on-demand searching and proactive update.

ZHLS (Zone-based Hierarchical Link State) Routing Protocol [37]

In ZHLS, the network is divided into non-overlapping clusters (*zones*) without any masters (*zone-heads*) as shown in Fig. 8(a). A node knows its physical location by geographic location techniques such as GPS. Thus, it can determine its *zone id* by mapping its physical location to a zone map, which has to be worked out at design stage. Each node periodically exchanges link state information, called *node LSP* (*Link State Packet*), with its neighbors and thus knows the local topology of its zone. For intra-zone routing, a shortest path algorithm is used for routing. For inter-zone routing, *zone LSP* is propagated globally throughout the network so that each node knows the zone-level topology and the next hop node toward every zone.

Given the zone id and the node id of a destination, the packet is routed based on the zone id till it reaches the correct zone. Then, in that zone, it is routed based on node id. Since the zone id of D changes due to mobility, the association of (D, zone id of D) can be obtained based on on-demand searching through the zone-level topology via gateway nodes. As discussed in Section 4.1, there are no masters in ZHLS but gateway(s) may exist between two zones. In Fig. 8(a), zones 4 and 5 have two pairs of gateways and zones 5 and 6 have a pair of gateways. However, it is possible for two nearby zones to have no gateways such as zones 2 and 5 in Fig. 8(a). In this case, the routing path consists of a number of inter-zone connections.



(a) ZHLS (b) GLS

Fig. 8. ZHLS [37] and GLS [38] protocols.

GLS (Grid Location Service) Protocol [38]

As in ZHLS, the GLS protocol provides a grid network based on physical locations. The basic routing principle used in GLS is *geographic forwarding*: The source *S* forwards packets toward the destination's physical location meaning that any intermediate node can determine whether it is along the direction between *S* and *D* by knowing the locations of *S*, *D* and itself and decides whether to forward or not [38]. Therefore, routing is essentially a two-step process: Find the destination node's location and perform geographic forwarding toward that location. In fact, geographic forwarding is used not only to route data packets but also to route location queries to masters that have location information of the destination.

As discussed in Section 4.1, GLS replicates the location information of a node at a small set of master nodes (*location servers*), where the set is different from node to node. For example, in Fig. 8(b), node *D*'s location information is maintained at nine masters. Node *D* periodically updates its location into those masters; three in order-1 squares, three in order-2 squares and another three in order-3 squares. (This in turn means that node *D* knows the locations of the nine master nodes and the location update is based on geographic forwarding.) When node *S* wishes to send data packets to *D*, it can query one of the nine masters about *D*'s location. While node *S* does not know master nodes of *D*, it can query to its masters, especially the most promising master which has the least id greater than node *D*'s id, hoping that it happen to have *D*'s location. Eventually, the query will reach a location server of *D* which will forward the query to node *D* itself. Since the query contains node S's location, it can respond directly using geographic forwarding.

5. Summary and Conclusion

Due to the increased path length between two end nodes in a multi-hop MANET, scalability is a challenging issue. A large-scale MANET is feasible only when the task of route search is localized so that the corresponding overhead does not increase as network grows. As one of the promising architectural choices for a scalable MANET, the *link cluster architecture* (*LCA*) was discussed, where mobile nodes are logically partitioned into clusters that are independently controlled and dynamically reconfigured with node mobility. By exploiting the spatial locality of communication in MANET applications, the clustered network architecture associated with hierarchical (inter- and intra-cluster) routing is more scalable compared to non-hierarchical ones. This paper classified and surveyed LCAs for MANET in terms of clustering algorithms and routing protocols.

Table 4 summarizes the cluster-based routing protocols with its routing principle and unique features.

Table 4. Comparison of cluster-based routing protocols.

LCA	Cluster-based protocol	Features	Route pattern	Inter-cluster routing principle
LCA for routing backbone				
LSG	CGSR [27]		S, M_S, G, ... G, M_D, D	Proactive update
	HSR [28]	Multilevel clusters		
	DSCR [27]		$S \Rightarrow M_D$, D	
	LANMAR [29]	Group mobility assumed for all nodes within a cluster		
	CBRP [30]	Joint gateways for better connectivity Unidirectional links considered	S, M_S, G, ... G, M_D, D (Route request packets follow a master-to-gateway routing path while actual data packets use a flat routing scheme toward M_D.)	On-demand searching
	ARC [31]	Multiple gateways between two masters for improved robustness		
LNG	SPAN [32]	LNG structure with small number of master nodes.	S, M_S, ... M_D, D	
	NTDR [33]	Asymmetric power model		
	GAF [34]	GPS-based clustering		
LCA for information infrastructure				
LLog	CEDAR [35]	QoS routing Unicast-based “core broadcast” for reliability	Flat routing principle	
	ZRP [36]	Every node being a master “Border-cast” through border nodes		
LGeo	ZHLS [37]	Zone-level routing via gateways		
	GLS [38]	A set of masters (location servers) for each node	Geographic forwarding	Hybrid

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