Does Cluster Architecture Enhance Performance Scalability of Clustered Mobile Ad Hoc Networks?

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Abstract— This paper explains and evaluates the performance of a cluster architecture-based routing protocol, called *Link Cluster Protocol (LCP)*, in *mobile ad hoc networks (MANETs)*. LCP shows better performance compared to one of the most popular ad hoc routing algorithm, called *Ad-hoc On-demand Distance Vector (AODV)*, for various network scenarios, particularly with the *clustered layout* of nodes. This node arrangement is more practical in many potential MANET application areas and is contrasted with the random layout that most of previous MANET research assumed. Even though nodes are not uniformly scattered, the underlying cluster architecture based on LCP algorithm constructs a number of clusters quite uniformly in the network area and thus the adverse effect of non-uniform node arrangement can be effectively avoided. We measured the packet delivery rate, delay, and control overhead for evaluating the LCP based on ns-2 network simulator and found that the major benefit comes the reduced routing control overhead especially around hot spots where nodes are overly cluttered.

Index terms - mobile ad hoc networks; node clustering; clustered architecture; network scalability;

I. INTRODUCTION

Wireless networks can be classified in two types: Infrastructured networks and infrastructure-less *mobile ad hoc networks (MANETs)*. Infrastructured network consists of a network with fixed and wired gateways, called based stations. A mobile host communicates with a base station in the network within its communication radius. The mobile host can move at any time while it is communicating. When it goes out of range of one base station, it connects with new base station and starts communicating through it. A MANET consists of a number of mobile hosts each of which can communicate with any other host through a dynamically computed route. MANETs are highly suitable for applications involving special outdoor events, communications in regions with no wireless infrastructure, emergencies and natural disasters, and military operations. Host mobility may be the most critical issue in a MANET, and thus previous research mostly focuses on routing or multicasting protocols that show consistent performance in the presence of wide range of mobility patterns.

A. *Demand for Scalable MANET*

As large-scale, high-density multi-hop network is desirable in many potential applications there exists a greater demand on scalable MANET architecture. The challenge is in the limited scalability despite the improved spatial diversity in a large network area. Effective bandwidth allowed per node decreases as network size grows [1]. This is mainly due to the increased route length between two end nodes in a MANET. Li *et al.* suggested that a large-scale multihop network is feasible only when most communication is local so that the path length does not increase as network size grows [2]. Grossglauser and Tse proposed an approach that each node localizes its data transfers by buffering the traffic until the destination node approaches within its radio range [3]. This solution however increases delay and requires a large buffer size at each node.

B. *LCA (Link Cluster Architecture) for a scalable MANET*

More general approaches for a scalable MANET have recently been explored in the literature [4]. Chen *et al.* proposed a forwarding backbone to reduce the number of control packets in a large-scale MANET [5]. Scalability to hundreds of thousands of nodes has been pursued by Morris *et al.*, where control packets are not flooded but directed to some particular positions [6]. Among them, *Link Cluster Architecture (LCA)* is one of the promising architectural choices for a scalable MANET [4]. Mobile hosts are logically partitioned into groups, called *clusters*; one host is chosen to perform the function of a master and some others to perform the function of gateways between clusters. Depending on the number of gateways between clusters, LCA produces overlapping or disjoint clusters. We classified them as: *LNG (LCA with no gateway)*, *LSG (LCA with a single gateway)* and *LPG (LCA with a pair of gateways)*.

Essentially, LCA divides an entire multi-hop MANET into a number of one-hop networks each of which has its own master node. Master nodes collectively maintain information on routing paths and nodes' association with clusters. LCA improves the scalability by reducing the routing-related control overhead. Other advantages are: Less chances of interference via coordination of data transmissions, and more robustness in the face of node mobility by judicially selecting stable nodes as masters.

C. Research Focus and Paper Organization

This paper considers the effectiveness of LCA in a MANET, in particular where node distribution is not random in space. While most of previous studies on MANETs assume *random layout* of nodes, it is quite possible in real scenarios that nodes gather in clusters rather than scatter at random. In other word, some subareas have concentration of nodes while others have a few or no nodes. This node placement is referred as *clustered layout* [7]. In concentrated subareas, severe interference happens due to heavy network traffic. In the sparse subareas, network connectivity is weak thus total network capacity is reduced by underutilization of the channel. According to previous study [7], the node distribution of the clustered layout contains a heavy tail unlike the traditional Poisson distribution, and can be modeled by a power-law distribution.

The main objective of this paper is to implement and investigate the effectiveness of an LCA algorithm, called *Link Cluster Protocol (LCP)*, particularly with the clustered layout. Based on *Ad-hoc On-demand Distance Vector (AODV)* routing algorithm [8], we implemented LCP in the context of *ns-2* network simulator [9]. According to the extensive simulation study, LCP performs on par with AODV with the random layout of nodes but shows significantly better performance than AODV with the clustered layout.

The organization of the paper is as follows. Section II overviews routing protocols and LCA for MANETs. Section III discusses the architecture of LCP and its implementation. Section IV presents the simulation results for comparing LCP with non-clustered AODV with the clustered layout of nodes. Finally, section V concludes the paper.

II. Previous work

A. Routing Protocols for MANETs

A large number of routing protocols have been developed for MANETs, which is characterized by unpredictable changes in network topology, node mobility, energy-constrained and memory-constrained mobile nodes, and bandwidth-constrained, intermittent wireless connections. While the routing problem has been well researched in infra-structured wireless networks, the solutions are more difficult to find in a dynamic MANET. Each of the routing protocols tries to effectively handle the problems of user mobility, bandwidth constraints, and resource constraints.

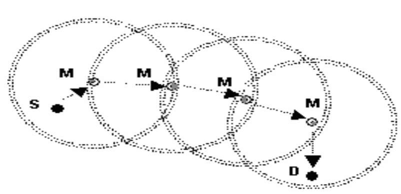
The routing protocols proposed MANET are generally categorized as table-driven, source-initiated on-demand, and hybrid based on the timing when the routes are updated. With the table-driven routing protocols, each node attempts to maintain consistent, up-to-date routing information to every other node in the network by responding to the changes in the network topology and propagating the updates. It is thus proactive such that when a packet needs to be forwarded the route is already known and can be immediately used. With source-initiated on-demand routing, routes are created only when they are desired by a source node. These are reactive protocols such that routes are created only when desired by the source node. Once a route has been established, it is maintained by some form of route maintenance procedure until either the destination becomes inaccessible along any path from the source or it is no longer desired. In contrast to table-driven routing protocols all up-to-date routes are not maintained at every node. The hybrid approach combines the table-driven approach and source-initiated on-demand driven approach such that locally table-driven but globally source initiated for minimizing the overhead incurred in route discovery and maintenance while maximizing the efficiency.

B. Link Cluster Architecture (LCA)

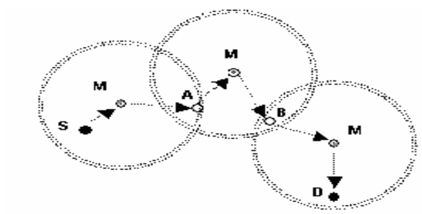
One of important design issues in abovementioned flat routing protocols is scalability. As network size grows and the number of mobile nodes increases, each node must maintain more routing information and participate more in data forwarding for other nodes' behalf. One possible solution is hierarchical routing based on *Link Cluster Architecture (LCA)*. In an LCA for a multi-hop MANET, mobile nodes are logically partitioned into groups, called *clusters*. The clusters should be 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 nodes to perform the function of gateways between clusters. The gateway node participates in two clusters and is under control of two master nodes with time-multiplexed manner. This network architecture has three main advantages. First, data transmissions are coordinated and separated in time in each cluster to reduce the chances of interference. Secondly, the cluster architecture is robust in the face of node mobility by judicially selecting stable nodes as masters. Finally, location management overhead can be greatly reduced with the help of master nodes. They collectively maintain network topology and provide information on routing path and node location [13, 14].

Figure 1 shows different cluster architectures with different level of cluster overlapping. Figure 1(a) depicts an LCA with no gateway (LNG). Here, master nodes perform the functions of gateways and they form a backbone network for routing so that most of traffic is traversed through the backbone. *NTDR (Near-Term Digital Radio)* networking [15] and *Span* [5] are examples of LNG. LCA with a single gateway (LSG) and a pair of gateways (LPG) in Figure 1(b) and 1(c) have shared gateway(s) between two clusters while LSPG in Figure 1(d) is the combination of the two. Note that clusters in LPG are non-overlapping. Cluster architecture for *ZRP (Zone Routing Protocol)* can be considered as an extension of the LPG because it can have more than two gateways between two master nodes [16]. *Scatternet* defined in Bluetooth is a typical example of LSG [17].

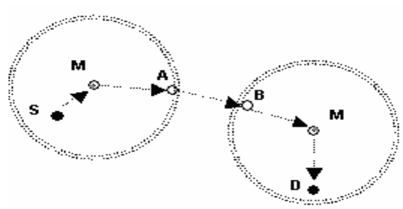
[1] Master nodes are alternatively called as *base stations*, *cluster heads* [10], *coordinators* [5] or a member of *dominating set* [11] or a *backbone network* [12].



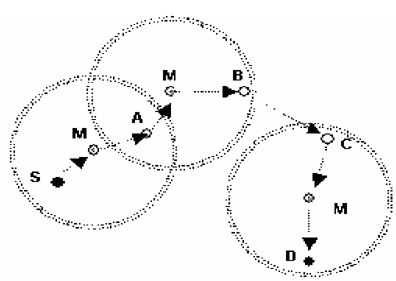
(a) LCA with no gateway (LNG)



(b) LCA with a single gateway (LSG)



(c) LCA with a pair of gateways (LPG)



(d) LCA with a single or a pair of gateways (LSPG)

Figure 1: LCA classification.

C. *Clustering Algorithms (Master Selection Algorithms)*

Clustering algorithms are critically important in cluster architectures since they deals with the problem of constructing the clustered subnets. They are also called as master selection algorithms because clustering is essentially a selection of masters among mobile nodes that have equal and symmetric capabilities. Each master candidate has a different set of nodes depending on the spatial location and the radio transmission range. Hence, electing a master node among a set of directly connected nodes is not straightforward. A clustering algorithm should be able to resolve conflicts in a distributed way when multiple mutually exclusive candidates compete. It must be able to dynamically reconfigure the cluster structure when some nodes move or some masters need to be replaced due to overloading. In the presence of mobility, it must preserve its cluster structure as much as possible and reduces the communication overheads to reconstruct clusters [13].

Maximal connection algorithm [11] is an LNG 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. *Span* algorithm [5] is a similar scheme but produces less number of master nodes. A node elects itself as a master if there are two unconnected neighbors either directly or via one or two masters. A randomized backoff delay is used to resolve contention. By definition, for each pair of nodes in two hops away, they are directly connected or there is a 2-hop or 3-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 an LNG network, even though the paths are not always shortest.

Scatternet defined in Bluetooth is a typical example of LSG [17]. The network is very robust against interference because each cluster in a scatternet, called *piconet*, uses a different communication channel from those used in nearby clusters based on the *frequency hopping spread spectrum (FHSS)* system. Therefore, between two clusters, there must be a gateway node that tunes to two different channels of the two clusters to serve as a gateway.

In order to make the routing algorithm scalable, *ZRP (Zone Routing Protocol)* [16] defines master nodes, or called *database nodes*, and let each of them maintain routing information around its *r-zone* which is within *r* hops away from the master node. It is an LPG algorithm and applies a proactive strategy inside the zone and a reactive strategy outside the local zone. Each node may be potentially located in many zones. The proactive *intra-zone routing protocol (IARP)* is an adapted distance-vector algorithm. When a source has no IARP route to a destination, it invokes a reactive *inter-zone routing protocol (IERP)* that is very similar to DSR.

In *identifier-based algorithm* [4], 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. By definition, a master node cannot have another master as a neighboring node and thus, this algorithm produces an LSPG structure. *Connectivity-based algorithm* [4] uses the node connectivity instead of node identifier to determine a master. When a tie happens, node identifier is used to resolve the conflict. In *randomized clustering algorithm* [15], a node elects itself as a master if it does not find any masters in its vicinity. Multiple candidates can compete to be a master and the conflicts are resolved by a random delay. When a node detects no masters in its neighbors, it first waits for a randomly selected time. If it still detects no masters after the delay, it now becomes a master and announces the fact immediately to its neighbors. This algorithm is logically the same as the identifier-based algorithm when the random wait time is translated to node identifier.

Adaptive clustering algorithm proposed in [13] forms disjoint clusters (LPG), each of which is assigned a different communication channel from those in neighboring clusters.

Without this assumption, the algorithm is equivalent to identifier-based clustering algorithm and it constructs the LSPG.

III. LCP

A. Clustered layout

Most of previous studies on MANETs rely on mobility models to generate nodes' movement as well as their geographical arrangements. One important observation is that all mobility models produce random layout of nodes at any instance of time during the simulation execution. This section considers a more realistic node arrangement in a MANET area, where node distribution is not random in space. The corresponding node arrangement is called *clustered layout* of nodes in contrast to random layout as discussed in Introduction. Recently, researchers began to notice the profound impact of node clustering on network performance [18, 19] and the topology generation methodology that produces clustered layout has been suggested [7]. This model is based on power-law distribution with heavy tail as in BRITE [20] that has been used to generate Internet topologies. Heavy-tail distributions have recently observed from many areas where the exponential distribution was traditionally assumed. It depends on the past memory unlike the exponential distribution that has a memory-less property.

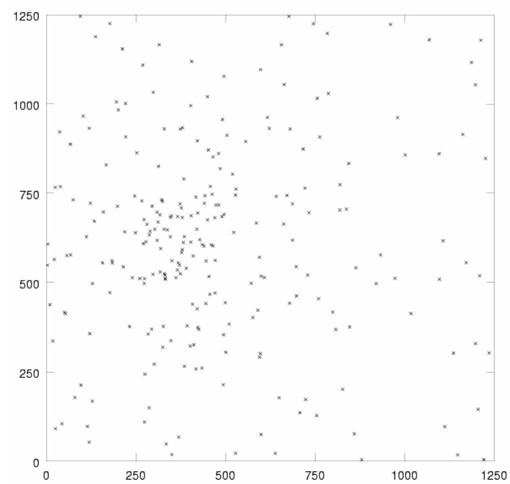


Figure 2: Clustered layout of 250 nodes in a 1250x1250m^2 MANET.

Fig 2 shows the clustered layout of 250 nodes over 1250×1250m ² area based on the aforementioned topology generation method in [7]. An entire network area is divided into a number of square subareas and the number of mobile hosts in each subarea is decided based on a given power-law distribution. A subarea that has a large number of nodes can be considered as a hot spot. This subarea contributes the shape of the heavy tail in the node density distribution. Once the number of nodes in a subarea is decided, they are randomly positioned within that subarea. In Figure 2, there is a hot spot in the left middle area of the network and thus node density would not be uniform across the network.

B. LCP implementation – clustering algorithm

In LCP, master nodes are decided by the degree of connectivity. A node that has the largest number of connected nodes among its *uncovered* neighbors is chosen as a master, where a node that is connected by a master node is said to be covered. If a tie happens, a node that has a lower identifier is selected as a master. Nodes that are covered by more than one master are gateway candidates. Among the gateway candidates, a node that connects the largest number of masters is selected as a gateway. This procedure continues until every master connects to at least one gateway in its direct communication range. A node that is neither a master node nor a gateway node is classified as a slave node. Figure 3 shows the resultant cluster architecture with a MANET in Figure 2. In Figure 3, masters are at centers of many spikes and gateways are between masters. It is important to note that even though nodes are clustered at the left middle area of the network in Figure 2, masters are quite uniformly distributed across the network as in Figure 3.

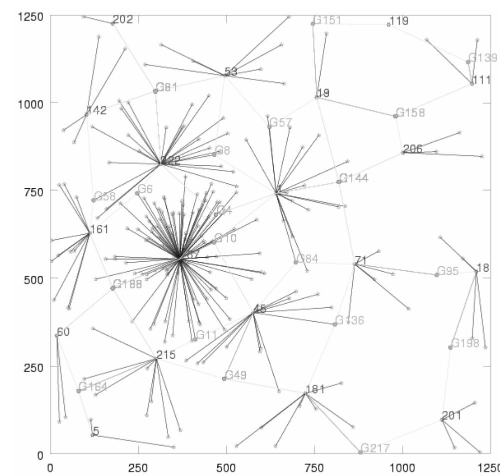


Figure 3: LCA construction of 250 nodes in a 1250x1250m^2 MANET using LCP. (Masters are at centers of many spikes and gateways are between masters.)

C. LCP implementation – data forwarding

In LCP, a data packet is forwarded from a source to its master first, and then to the next master via a shared gateway, and so on until it reaches the final destination. LCP is implemented on top of AODV algorithm and routing paths are searched based on AODV principle. However, since master nodes have information of its clusters and its member nodes, control packets implementing the AODV such as *RREQ (Route Request)* [8] is only handled by masters. When a node receives a RREQ packet, it either ignores the packet (if it is a slave) or processes the packet (if it is a master) depending on its role under the link cluster architecture. That way, control overhead in a flat routing protocol, which is usually caused by broadcasting of control packets, can be greatly reduced.

In summary, a master node drops the packet from a sender if the sender does not belong to its cluster. Otherwise, it processes normally by passing the packet to AODV. A gateway processes a packet normally only if the sender is a master that the gateway belongs to. A slave node drops most of the packets unless it is the intended receiver. Figure 4 shows the pseudo code of the LCP procedure.

LCP renders a routing path a bit longer than the original AODV. However, since the packet link delay between two nodes is negligible, taking more hops does not mean longer delay. Under the wireless environment with random medium access methods, most of delays come from collisions among multiple senders.

```
Upon receiving a packet (sender S, receiver R)
at node N with its master M
{
if (N is a MASTER)
    if (S belongs to N)
    ; a slave sends a packet to a master
            pass the packet to AODV;
    else
            drop the packet;

or if (N is a SLAVE)
    if (N is R) && (S is M)
    ; my master sends me a packet
            pass the packet to AODV;
    else
            drop the packet;

or if (N is a Gateway)
    if (S is M)
    ; my master sends a packet
            pass the packet to AODV;
    else
            drop the packet;
}
```

Figure 4: Pseudo code of LCP procedure.

IV. PERFORMANCE EVALUATION

A. *Simulation model*

To see the effectiveness of LCP (Figures 3 and 4) with the clustered layout (Figure 2), an extensive simulation study has been conducted based on ns-2 network simulator [9]. It is an object oriented and discrete event driven simulator, written in C++ with an Otcl interpreter as a front-end. Physical activities are translated to events and events are queued and processed in the order of their scheduled occurrences. It simulates node mobility, physical layer, radio network interfaces, and the IEEE 802.11 MAC protocol.

The performance evaluation is based on simulation of 250 static mobile nodes distributed on an area of 1250×1250m² as in Figure 2. The simulation area is divided by 25 subareas and each subarea has predetermined number of nodes. A power-law distribution is used to determine the number of nodes in each of 25 subareas as discussed in Section III.A. The radio transmission range is 250m and a *two-ray ground propagation channel* is assumed with data rate of 1 Mbps.

Constant bit rate traffic (CBR) is used for data traffic. 512-byte data packet is generated every 0.001 ~ 0.5 from 100 CBR sources out of 250 nodes. Source-destination node pairs are randomly selected. Several runs are repeated with different source-destination pairs for the same number of CBR traffic sources to obtain average performance measures.

Three important performance metrics are evaluated: *Packet delivery ratio* is the ratio of the data packets delivered to the destinations to those generated by the CBR sources. *Average end-to-end delay of data packets* includes all possible delays caused by buffering during route discovery latency, queuing at the interface queue, retransmission delays at the MAC, propagation and transfer times. Finally, *protocol overhead* is total number of control packets that are used for route discovery and maintenance.

B. *Simulation Results and Discussion*

Figure 5 compares the packet delivery ratio of LCP and AODV with the clustered layout. As we can see in the figure, LCP performs better than AODV for most of the ranges. In a heavy traffic environment, LCP performs far better than AODV. However, it is not true when traffic is light. This is simply because LCP extends the number of hops by having masters and gateways along the routing paths and it increases traffic for delivering data packets. It is noted that LCP aims at reducing the control overhead and thus it may not be as efficient as expected when traffic is light.

This is also shown with the average packet delay in Figure 6. LCP has less delay than AODV independent of network load but the advantage is more significant when traffic is heavy. When the offered traffic is 0.5 Mbps, the average delay is six times lower than AODV.

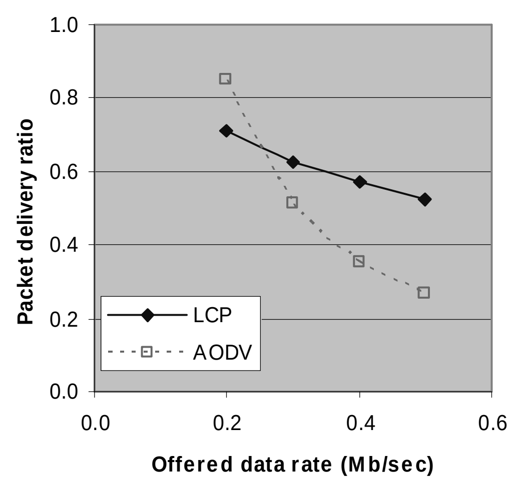


Figure 5: Packet Delivery Ratio.

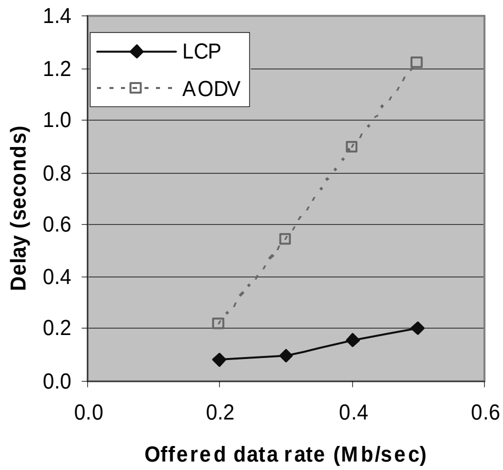


Figure 6: Average packet delay.

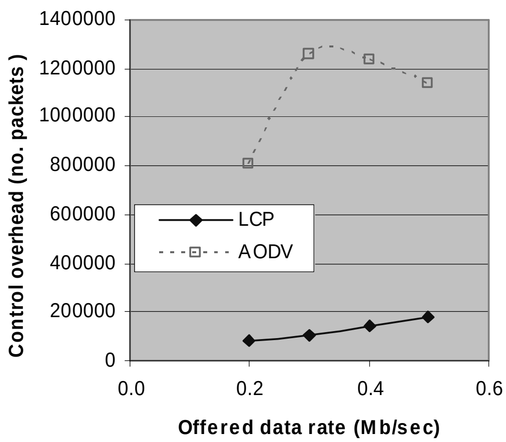


Figure 7: Control overhead in terms of the number of control packets.

Superiority of LCP over AODV mostly comes from the reduced control overhead as discussed in Section III. Figure 7 shows the control overhead measured by the number of control packets such as RREQ. Since only the master and gateway nodes participate in broadcasting the RREQ packets, LCP shows much less overheads than AODV for all simulation ranges as shown in Figure 7.

V. Conclusion

The simulation results indicate that LCP is advantageous over AODV with the clustered layout. By constructing a cluster architecture based on LCP algorithm, we have achieved a significant improvement in packet delivery ratio and packet delay. Also, it has been shown that this improvement mostly comes from the reduction in control overhead. Since packet delivery ratio directly relates to network capacity, this result gives insight to design direction how to further improve network capacity. At the same time, LCP and the related cluster architecture can be used to improve scalability when designing large scale MANETs.

The knowledge acquired from this research can be used for improving an algorithm for cluster network. The performance evaluation of LCA based algorithm under clustered layout will show other aspects of LCA based MANET algorithm. These new facets of algorithms will lead to an insight to designing better algorithms for MANET. For future research, we are going to add mobility into the simulation. We are also investigating the adaptive clustering algorithm, which converts a small size cluster to several singleton clusters.

VI. Acknowledgement

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