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Adaptive Cluster-based Approach for Reducing Routing Overheads in MANETs*

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Abstract—**Despite the substantial work done on Mobile Ad Hoc Networks (MANETs), the scalability of routing protocols remains a limiting factor in large-scale deployments. An inherent problem lies in the route discovery mechanism of routing protocols, most of which rely on some form of flooding to search for routes and disseminate topology information. Clustering has been identified as one of the approaches to improve routing protocols' scalability and can prove to be useful provided the additional overheads incurred by the clustering management do not negate the gains in the reduction of routing overheads. In this paper, we present an extension of a typical MANET routing protocol that integrates an adaptive clustering mechanism and show that it is able to significantly reduce the communications overheads of routing protocols, thus paving the way for greater scalability.**

Keywords-MANET; clustering; routing overheads;

I. INTRODUCTION

The US Department of Defense, in particular DARPA, pioneered the research in mobile ad hoc networks (MANETs) with the deployment of Packet Radio Network (PRnet) in 1972 [1]. The motivation of PRnet, later known as MANETs, is to relieve the network from relying on base stations due to the fact that the deployment of base stations is difficult and almost impossible in hostile environments. Furthermore, the network is subject to failure if one or several base stations are destroyed. Node mobility is also limited as the mobile nodes must be in the transmission range of base stations. On the other hand, MANET, with its distributed network architecture and broadcast radio, is more suitable for the military deployments. To overcome the limited radio transmission ranges, nodes are equipped with the ability to act like a router and to forward information on behalf of others, i.e. multi-hop communications. Subsequent DARPA projects like SURAN in 1983 [2], Global Mobile Information Systems program in 1994 [3], and the Land Warrior program [4] and its deployment [5] involve a larger number of mobile devices and a wider region. Apart from military applications, large-scale commercial applications of MANETs also began emerging with the proliferation of wireless technology. Envisioned large-scale commercial applications include smart vehicular system and a radio dispatch system for public transportation system [6].

As the scale of MANETs continues to grow, one of the most critical design elements of MANET protocols is their applicability in large-scale deployments, i.e. the protocol scalability [7][8][9]. Forming a logical hierarchical network organization by clustering is pointed out by [9] as one of the common approaches to increase protocols' scalability and three enhancements have been proposed, namely, Expanding Ring Search (ERS), query localization and local repair, for the Ad hoc On-demand Distance Vector (AODV) routing protocol [10] in order to increase its scalability. Protocol scalability of baseline AODV and its further enhancements were evaluated via network simulations in [9]. It has been shown that the use of local repair could increase the number of data packets delivered to the destinations. ERS and query localization techniques seem to further reduce the amount of protocol control overhead generated by the protocol, by limiting the number of nodes affected by route discoveries. All these three proposed enhancements intend to reduce network-wide flooding of control packets invoked in AODV protocol during route discovery or re-discovery. However, despite being mentioned, a clustering approach has not been provided.

Many of the proposed MANETs routing protocols use a broadcast route discovery mechanism whereby a route request is flooded across the entire network. While the impact of such network-wide broadcast may be limited in small networks, it is significantly greater for larger networks and this phenomenon is known as a broadcast storm [11]. This paper examines the potential of using a pre-existing cluster structure to enhance the scalability of routing protocols by attempting to limit the impact of network-wide flooding in MANETs. Clustering has been regularly proposed as a means to improve scalability in MANETs and a good survey of clustering algorithms can be found in [12]. However, clustering in MANETs does not come without any cost to the network. Cluster management schemes often, if not always, introduce new control messages into the network that compete with the other network traffic for the limited wireless bandwidth. If not managed properly, cluster management messages can easily overwhelm other network traffic, making the network essentially useless. Very often, clustering algorithms are assessed based on metrics that only consider the cluster characteristics without taking into consideration how the more important data traffic has been affected, e.g. [13], [14]. Typically, cluster stability (lifetime) and cluster size are two common metrics used to evaluate the performance of clustering algorithms. What is the benefit of having a stable cluster if the performance of the data (application) traffic does not improve? Worse, the additional cluster management traffic competes with the data traffic for

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the limited bandwidth and starves data traffic. Another pertinent question is the optimal cluster size or conversely, the number of clusters formed. It has often been claimed that smaller clusters are better without providing any justification on why it is better with regards to the overall network performance.

In this paper, we aim to study the effects of clustering and how it can improve network performance. The main objective is to free up more wireless bandwidth by reducing routing control overheads without adversely affecting network performance. While there are numerous MANET routing protocols, the AODV protocol is used as a representative of on-demand routing protocols because it has been ratified by the Internet Engineering Task Force. While various clustering algorithms have been proposed for use in MANETs [12], we have selected the Mobility-based D-Hop (MobDHop) clustering algorithm [15] as a candidate for our study because it forms stable multi-hop clusters and adapts to the mobility pattern of the nodes to form a two-tiered logical hierarchical network structure. In this paper, we combine AODV with MobDHop into a new variant of the AODV protocol, namely MobDHop-AODV. MobDHop-AODV works on top of the cluster structure formed by MobDHop and utilizes the cluster membership knowledge of clusterheads to avoid unnecessary network-wide flooding in MANETs. We Simulation studies were conducted to verify the effectiveness of MobDHop-AODV and it is shown that around 25% to 75% control overhead savings can be achieved, over and above the additional overheads introduced by the clustering mechanism.

II. BACKGROUND AND RELATED WORK

A. *AODV*

The Ad hoc On-demand Distance Vector (AODV) routing protocol is a reactive unicast routing protocol that constructs and maintains unicast routes in MANETs. It avoids routing loops by introducing the use of sequence numbers. There are three types of control messages used by AODV: Route Request (RREQ) messages are initiated from the source node when it needs to send data to a destination node which it does not have a valid or existing path. Each node that receives the broadcasted RREQ message will update its routing table with the knowledge of route to source node and rebroadcasts it. Route Reply (RREP) messages will be initiated by either the target node or intermediate nodes if the latter has a valid route to the destination that is “fresh enough”, based on the sequence numbers. Route Error (RERR) messages are used to notify the other nodes which use routes have broken links while link connectivity information is maintained by periodical broadcast of Hello messages.

B. *MobDHop Clustering Algorithm*

The Mobility-based D-Hop (MobDHop) clustering algorithm forms adaptive and stable multihop clusters. It is designed to form d-hop clusters that have flexible cluster diameters. The parameter d is user-defined, which can be adjusted to meet a desired cluster density. Each cluster's members are at most d-hops away from the clusterhead but the diameter of clusters is not necessarily $2d$; it is at most $2d$. Instead, it is adaptive to the group characteristics and mobility pattern of network nodes.

First, MobDHop forms non-overlapping one-hop clusters where each cluster member is at most one hop away from its clusterhead. The election of the clusterhead is based on two mobility metrics: (a) variation of estimated distance between nodes over time (*VD*), and (b) estimated mean distance for cluster (*EMD*). Each node computes a local stability value by taking all neighbours' *VD* values into consideration. This value implies how stable a node is with respect to all immediate neighbours, and a node with the lowest (best) stability value assumes the role of clusterhead and announces it with a Hello message. Neighbour nodes assume the role of ordinary members. If a cluster member can hear Hello messages from more than one cluster, it assumes the role of a gateway.

Next, a merging process will be initiated by a non-clustered node to join the neighbouring cluster. A node may become non-clustered when it is newly activated or it loses its clusterhead due to node mobility. The merging node will first observe its neighbourhood and choose the neighbour to which it is most stably connected. Then, it will try to merge into its neighbour's cluster if the following conditions are met:

- Hop count from merging node to its new clusterhead is less than the predefined parameter, d.
- The stability value of the link between the merging node and its chosen neighbour should be lower than the overall stability value of the cluster.

The second condition ensures that the newly formed cluster achieves a required level of stability by taking their *VD* and *EMD* into consideration. After the merging process, a valid cluster structure should be achieved. Such a valid condition is defined by the following properties: (1) every ordinary or gateway node has at least one clusterhead as its d-hop neighbour and (2) clusterheads cannot be direct neighbours of each other. Each node reacts to the changes in the surrounding topology and changes its status or cluster membership accordingly for cluster maintenance. It has been shown in [16] that the overheads incurred by multihop clustering has a similar asymptotic bound, i.e. $O(1)$ as one-hop clustering while being able to reap the benefits of multihop clusters.

III. MOBDHOP-BASED AODV

A new variant of AODV, namely MobDHop-AODV, is introduced to work on top of the stable, two-tier cluster structure formed by the MobDHop clustering algorithm. The goal of this protocol is to exploit the aggregated topology information stored at every clusterhead to avoid the need to flood the network with route request (RREQ) packets in the search for intended destinations.

A. *MobDHop-AODV*

In MobDHop-AODV, two extra protocol messages are introduced, viz., Cluster Request (CREQ) and Cluster Reply (CREP) messages. CREQ is initiated from the source node when it needs to send data and the route to destination is still unknown. The source node first sends a unicast CREQ message to its clusterhead, which upon receiving the CREQ message, will check its membership table for the destination node.

Cluster Reply (CREP) will then be sent by the clusterhead back to the source. If the destination node is found in the cluster, a Boolean flag, *InCluster*, in the CREP message is set to true. At the same time, the clusterhead will initiate a RREQ packet to the destination node in order to set up a path. If the destination node is not found in the cluster, the *InCluster* flag is set to false. Upon receiving the CREP message, the source will check the value of the *InCluster* flag. If the flag indicates a true value, the source node will transmit data packets by using the path set up during the propagation of CREQ message. Otherwise, the source node will initiate a network-wide flooding of RREQ message to search for the route to destination node.

This additional routine will reduce the number of network-wide RREQ messages initiated by the source node if both the source and destinations nodes belong to the same cluster. The possibility of having broadcast storms [11] can be reduced and the limited resources such as channel resources and device resources in MANETs can be preserved. By reducing control traffic, more data traffic can be transmitted over the network.

B. *Control Overhead Savings*

MobDHop-AODV will reduce the volume of network-wide route discovery and reduce the amount of control overhead incurred in the network if there exist traffic between two cluster members in the same cluster, which is also known as intra-cluster traffic.

If intra-cluster traffic is dominant in the network, the potential savings in terms of control overhead by using MobDHop-AODV are immense. For example, let

- t_1 be the number of intra-cluster traffic connections
- t_2 be the number of inter-cluster traffic connections
- m be average cluster size
- N be total number of nodes in the network
- h be maximum cluster radius

During route discovery process, RREQ message will be flooded in the AODV protocol each time a traffic connection is established. For each discovery process, every node will at least transmit RREQ message for once. Therefore, the total number of RREQ transmitted is $(t_1+t_2)\cdot N$ in the AODV protocol. In MobDHop-AODV, the total number of RREQ, CREQ and CREP transmitted during route discovery process is given by the following equation:

$$2\cdot h\cdot t_1+\left(\frac{N}{m}\right)\cdot t_1+N\cdot t_2 \tag{1}$$

If 80% of the traffic in a 200-node network is intra-cluster traffic, the savings of control overhead by using MobDHop-AODV is about 75% assuming $m = 20$.

IV. SIMULATION RESULTS AND DISCUSSIONS

Simulations were conducted by using Qualnet 3.8. The communication range is about 376 metres which is the default setting for IEEE 802.11 DCF with channel capacity of 2Mbps in Qualnet. For each network configuration, ten different scenarios were generated using randomized seed values, and each data point is the average from ten simulation runs. In these simulations, 200 nodes were simulated over an area of 2000 metres by 2000 metres. Nodes move according to the Reference Point Group Mobility (RPGM) model whereby each group has a logical centre (group leader), which determines the group's motion behaviour. Initially, each member is uniformly distributed in the neighbourhood of the logical centre, and subsequently, every node randomly moves with certain speed and towards certain direction with respect to the movement of its logical centre. However, each node may deviate from its group leader in speed, direction and distance, according to some predefined parameters. The average node speed was varied from 0 m/s to 20 m/s. Each mobility group consisted of 20 nodes and the maximum group deviation distance was set to 500 metres. The duration of each simulation was 600 seconds. All MobDHop parameters were similar to those used in Table I. Each source starts to generate Constant Bit Rate (CBR) traffic at the rate of two 512-bytes data packets per second for 300 seconds. The starting instances were randomly chosen between 0-300 seconds. We simulated two traffic scenarios consisting of 20 and 30 connections respectively.

TABLE I. ALGORITHM PARAMETERS FOR MOBDHOP

Parameter	Meaning	Value in Simulation
BI	Broadcast Interval	0.75-1.25 sec
TD	Discovery Interval	BI * 6
TA	Assignment Interval	BI * 2
TM	Merge Interval	BI * 2
TC	Contention Period	BI * 2
MaxHop	Maximum Hop Count From Clusterhead	2

A. *Performance Metrics*

The performance of MobDHop-AODV and the AODV protocol were compared using the following metrics:

- Packet Delivery Ratio: The number of data packets successfully delivered to destinations over the number of data packets should be delivered to destinations.
- Number of RREQ Transmitted: Total number of RREQ messages transmitted by the source and intermediate nodes.
- Number of Routing Control Packets Transmitted: Total number of control packets transmitted by source, destination and intermediate nodes for unicast routing purpose. For AODV, these control packets include RREQ, RREP and RERR. For MobDHop-AODV, these control packets include RREQ, RREP, RERR, CREQ and CREP.
- Average End-to-End Delay: The average duration from the time at which a data packet is generated and the time at which it is received by the destination.

B. Results and Discussions

Figure 1 and Figure 2 show the packet delivery ratio of MobDHop-AODV and AODV with respect to the increase in average node speed for 20 and 30 connections respectively. Packet delivery ratio of both schemes decreased with the increase in average node speed as the topology is more dynamic in the network of higher mobility rate. The packet delivery ratio of MobDHop-AODV was comparable to the packet delivery ratio of the original AODV. As depicted in Figure 1 and Figure 2, the packet delivery ratio of AODV in a static network (network with 0m/s average node speed) was lower than MobDHop-AODV. Since there is no mobility in static network, the considerable packet loss in AODV could only be due to the serious contention and collisions at MAC layer between data and control packets. It was observed in Figure 5 that the routing control packets incurred by AODV in static networks was about three times higher than those incurred by MobDHop-AODV.

Figure 3 and Figure 4 show that MobDHop-AODV successfully reduced the total number of network-wide RREQ messages sent by 20-75% over scenarios of different speeds and traffic load. This is attributed to the fact that MobDHop-AODV introduces an extra routine that requires source node to make a query to its clusterhead for the location of destination before initiating a network-wide flooding of RREQ messages. If the destination is located inside the same cluster as source node, unnecessary network-wide flooding of RREQ messages can be avoided. MobDHop-AODV also transmitted much fewer routing control packets over the network of different average node speed as shown in Figure 5 and Figure 6. The significant reduction in routing overhead can increase the ability of MANETs to support more unicast traffic or other types of traffic in the network.

Due to the additional intra-cluster request cycle in MobDHop-AODV, extra latency will be incurred during the route discovery phase. This is evident in Figure 7 and Figure 8 that MobDHop-AODV incurred higher average end-to-end delay because of the additional clusterhead query routine. The impact of extra latency introduced by MobDHop is less significant in static networks (networks with 0m/s average node speed) as the routes in static networks seldom break. Therefore, there is no need to initiate frequent route query, either intra-cluster CREQ or network-wide RREQ to search for destinations.

V. CONCLUSION

Scalability remains a key issue in MANETs despite the vast amounts of work done. MANET routing protocols rely largely on a broadcast-based route discovery mechanism whereby route request messages are flooded across the entire network in search of routes to send packets. This approach does not have a significant impact on small networks but as the network size grows, the communication overheads (leading to a broadcast storm) soon consume a large portion of the shared wireless bandwidth, leaving little for the actual data traffic. Among the many proposals addressing the scalability problem, clustering has been identified as a good candidate for creating multi-tier network structures that can limit network-wide flooding of routing control messages. Clustering does not come without costs as cluster setup and management requires periodical exchange of control messages among nodes. However, if managed properly, substantial reductions in routing control overhead can be achieved.

In this paper, we have integrated MobDHop, which is an adaptive clustering scheme, with AODV and demonstrated through simulations that substantial reduction in control overheads is achievable by limiting network-wide broadcast of route discovery messages. This approach paves way for greater scalability of MANET routing protocols and large-scale deployment. Further improvements to this approach involve viewing clusters as super nodes and applying the route discovery process on these super nodes for communication between nodes in different clusters.

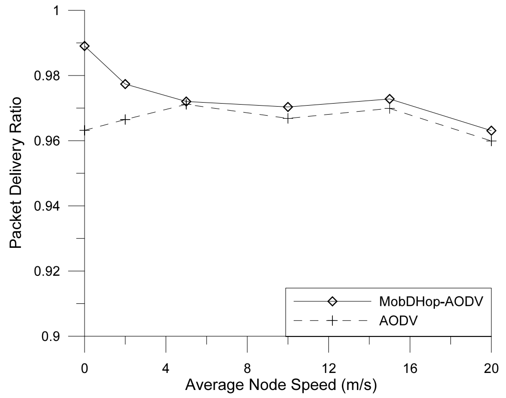

Figure 1. Packet delivery ratio (20 connections)

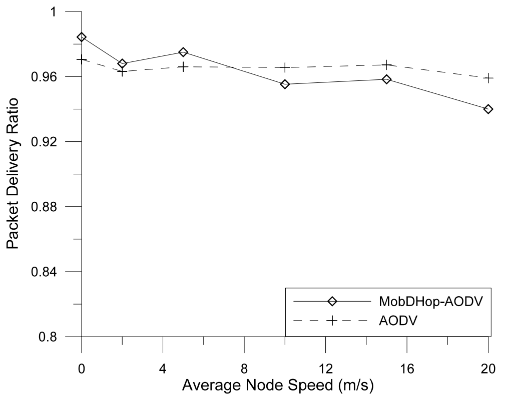

Figure 2. Packet delivery raio (30 connections)

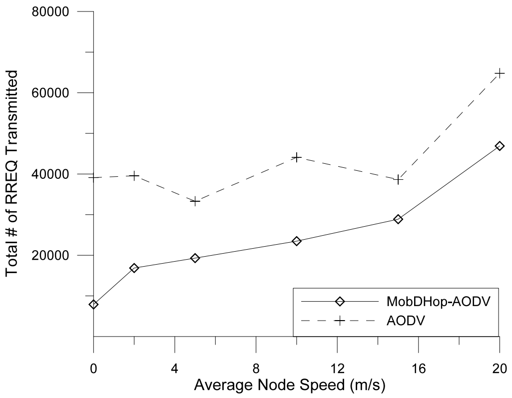

Figure 3. Total number of RREQ transmitted (20 connections)

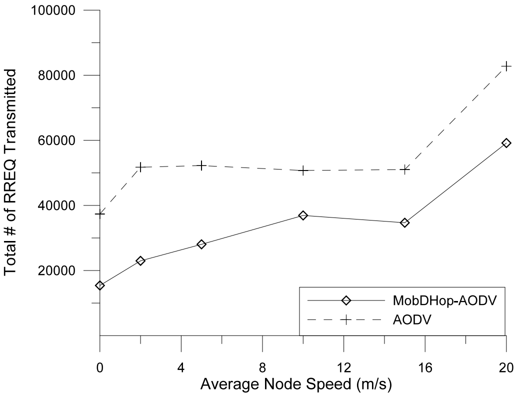

Figure 4. Total number of RREQ transmitted (30 connections)

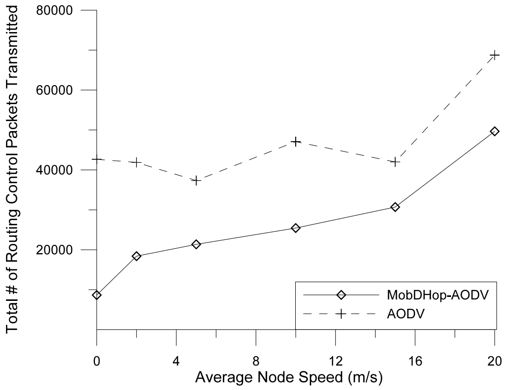

Figure 5. Total number of routing control packets transmitted (20 connections)

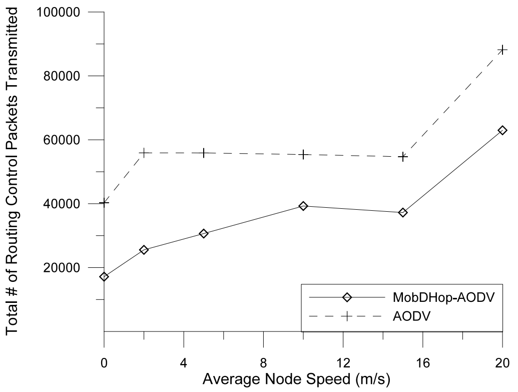

Figure 6. Total number of routing control packets transmitted (30 connections)

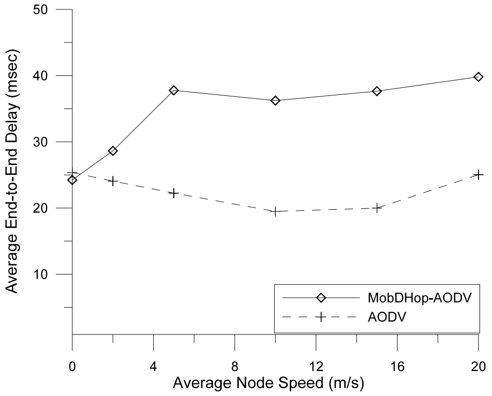

Figure 7. Average end-to-end delay (20 connections)

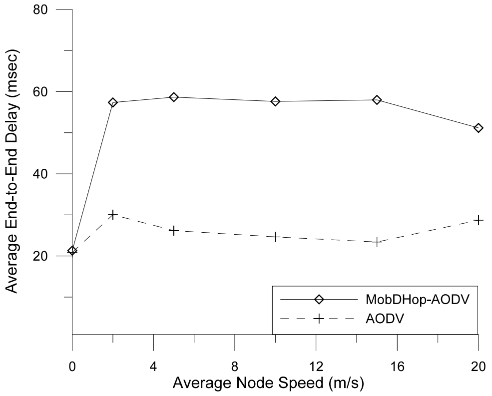

Figure 8. Average end-to-end delay (30 connections)

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