Abstract—Inter-domain routing for MANETs (Mobile Ad Hoc Networks) draws increasing attention in military and civil application. It works on heterogeneous networking protocols, including different MAC layer protocols and routing layer protocols. It elects gateways within each domain, which in turn connect to other domains.

In this paper, we propose several techniques to improve the performance of inter-domain routing. One key innovation in this paper is MPR-aware dynamic TDMA protocol. MPR (multipoint relay) information is exchanged to optimize the slot allocation algorithm and indirectly improve inter-domain performance. Another contribution of this paper is a new gateway election algorithm that accounts for TDMA performance and for connectivity with a CSMA domain. The proposed algorithm also exploits the MPR method embedded in OLSR intra-domain routing protocol, to get the knowledge of network topology and improve TDMA performance and gateway election.

Simulation experiments show significant improvements in connectivity, inter-domain throughput and the reduction of control overhead.

Keywords- gateway election, inter-domain routing, MPR-aware dynamic TDMA

I. INTRODUCTION

Nowadays, with the development of military and civil applications, inter-domain routing for Mobile Ad Hoc Networks (MANETs) draws increasing attention. Inter-domain routing in heterogeneous MANETs is not easy. The challenges include dynamic network topology, intermittent connectivity, membership management, routing protocol and link layer protocol heterogeneity. To meet the above challenges, researchers have proposed several Inter-Domain Routing (IDR) Protocols for MANETs to achieve scalability and robustness using cluster techniques [1]. Moreover, when the link layer protocols are different, like CSMA and TDMA, the gateway between these different domains must be equipped with multiple interfaces working on CSMA protocol and TDMA protocol individually.

In this paper, we show that TDMA is the weakest link in inter-domain routing and propose a MPR-aware Dynamic TDMA protocol and a MPR-aware Inter-Domain Routing gateway election algorithm to boost the throughput of TDMA. We show that this greatly improves also the performance of inter-domain routing between CSMA and TDMA domains. We implemented in Qualnet simulator the MPR-aware Dynamic TDMA protocol that takes MPR information from OLSR [2] routing protocol to optimize the slot allocation algorithm in the Inter-domain Routing scenario. We also implemented a new MPR-aware gateway election algorithm which accounts for both transmission efficiency and node distribution to reduce the control overhead and improve the performance of Inter-domain routing protocol.

The rest of the paper is organized as follows. Previous work is briefly reviewed in section II. Then we describe the design of our MPR-aware TDMA and IDR protocol in details in section III. Results from extensive performance experiments are presented in section IV. We conclude the report and point out the future work in section V.

II. RELATED WORK

A. Geo-based Inter-domain Routing Protocol

Previously we proposed a Geo-based Inter-Domain Routing protocol (GIDR) [1] [3]. The basic structure of GIDR is clusters and gateways in each domain. We implemented GIDR into a heterogeneous inter-domain routing scenario in Qualnet simulator [4].

In the following simulation scenario as shown in Figure 1 and 2, there are two domains in a mobile ad-hoc network. In Figure 1, Domain 1 runs the AODV [5] routing protocol and the CSMA MAC protocol; domain 2 runs OLSR and CSMA MAC. In Figure 2 we have the same scenario, except for TDMA MAC protocol in Domain 2. GIDR uses Geo-DFR as its basic routing method under the inter-domain routing layer.

B. Three Categories of TDMA

There are basically three categories of TDMA – Static TDMA (STDMA), Dynamic TDMA (DTDMA) and Cluster TDMA (CTDMA) [6] [7] [8] [9] [10].

B1. Static TDMA (STDMA)

STDMA cuts the channel into individual static time slots for different transmitters. Scheduling can be done automatically or
manually, but cannot change dynamically. In automatic scheduling, slots are assigned to nodes on a round-robin basis. In manual scheduling, the user can specify a configuration file containing the predefined schedule. However, both automatic and manual scheduling schemes allocate slots at the very beginning of the simulation and cannot be changed in real time.

B2. Cluster TDMA (CTDMA)

CTDMA uses a distributed clustering algorithm to organize nodes into clusters. The cluster heads are local coordinators and resolve channel scheduling, perform power measurement/control, maintain time division frame synchronization, and enhance the spatial reuse of time slots and codes.

B3. Dynamic TDMA (DTDMA)

DTDMA dynamically reserves a variable number of timeslots per frame for different rate streams based on their traffic demands. Advantages include slot reuse and the ability to reserve one or more additional slots to serve different QoS delivery, as a difference of only one slot in STDMA [6] [7].

III. MPR-AWARE DYNAMIC TDMA AND INTER-DOMAIN ROUTING PROTOCOL

In this paper, we proposed a MPR-aware Dynamic TDMA and MPR-aware Inter-domain Routing protocol exploiting the OLSR intra-routing protocol. The goal is to improve the TDMA MAC layer performance in heterogeneous Inter-domain Routing scenarios.

Considering Figure 1 example, and assuming link capacity =2Mbps, we increase the sender’s bit rate to test the throughput of the network. From the simulation result of the GIDR protocol, the performance is illustrated in Figure 3.

The maximum throughput of these two CSMA domains can reach about 1.5Mbps. This is reasonable under 2Mbps link capacity.

However, if we consider Figure 2, with the TDMA MAC protocol, the throughput from CSMA domain to TDMA domain in Figure 2 significantly drops – maximum is around only 180Kbps.

The drawback of the above STDMA is obvious due to its inefficient slot usage. In another example, in Figure 5, suppose there are 14 nodes in the TDMA domain. Node 2 is in transmission mode and the rest of the nodes are in receiving mode or idle. Note that node 14 is neither one-hop nor two-hop neighbor of node 2. Even if node 14 can transmit without colliding with any of its one or two hop neighbors, according to the STDMA protocol it must wait in receiving or idle mode. Same thing happens on every node beyond the neighborhood of the currently transmitting node. This causes slot waste and low performance.

To boost performance, we have to come up with a solution that allocates slots according to network topology and the contention area of each node. We will review several DTDMA options in section III before presenting our final solution.

We choose DTDMA because CTDMA has the following disadvantages:

- Link throughput calculation does not take into account data slot collisions, silence gaps, and control overhead, so simulation cannot produce accurate results.
- Broken call probability of CTDMA increases with radio speed and call duration. This probability is intolerable under high radio speed.
- CTDMA does not provide efficient ACK handling.

Based on the discussion above, DTDMA is more suitable to be implemented into MANET, and we have the following three options:

- Frame length stays the same while slot duration varies.
- Frame length stays the same while slot allocation is based on the contention area.
- Frame length varies dynamically along with the slot allocation based on the contention area.
In the first approach, time slots are allocated for the entire network initially while keeping the frame length constant. If we omit guard time in between two slots and inter-frame time, we have the following formula (1). When a new node joins, the slot duration is changed within the same frame length, that is, the earlier slot duration decreases.

\[ \text{frame length} = \text{number of time slots} \times \text{slot duration} \]  \hspace{1cm} (1)

The major disadvantage of this approach is that slot duration is physically lower bounded and hence the number of nodes is restricted. Beyond a certain point, it is not possible to add more nodes.

In the second approach, initially the contention area of each node is determined, and slots are allocated only for the nodes in that contention area. Hence many time slots are not used. When a new node joins, it is allocated the unused time slot; hence the problem of reducing slot size is relaxed. As shown in Figure 6, the concept of slot allocation based on the contention area is used. Initially, while node 1 is in transmission mode, the contention area (node 1’s two hops area) is determined and is found to be consisting of 6 nodes. Each node in that area is allocated one time slot, whereas the rest of the frame remains empty. Whenever a new node, for example node 15 comes in the contention area, it is assigned one of the empty slots in the frame, without affecting the duration of the other time slots of the contention area. The disadvantage of this approach is that the unused slots are wasted.

The last approach [11][12] is the technique proposed in the paper. The frame length is initially the same as the contention area (more precisely, frame length is power of 2, as explained in section A). As a new node joins, the frame length is dynamically increased by adding a new slot to it. The number of slots can vary but the slot duration stays the same. Using the same scenario as in Figure 6, initially the contention area consists of 6 nodes; hence the frame length is calculated accordingly, giving each node 1 time slot. When a new node, for example node 15 joins the contention area, the frame length is dynamically increased by adding one more time slot to the frame for node 15 (actually the frame length will increase to the next power of 2, but for simplicity we can imagine the frame with length 15 in this section). As we will show, this approach removes all the disadvantages of the previous approaches, and no slots are wasted.

The frame length is a power of 2. So, the frame length for a particular node will be 2 or 4 or 8 or 16 (2^1, 2^2, 2^3, 2^4 and so on) as shown in Figure 7. It is to be noted that different nodes in the network can have different frame lengths. The reason for this choice will become clear as we explain the working of the protocol in detail. In every frame, there is a slot (i.e. Slot 0) reserved for new nodes for sending control packets. As a new node enters the network it can send control packets to all the neighboring nodes in slot 0 and request the slot assignment information from them.

\[
0 \quad 1 \quad 2 \quad 3 \quad 0 \quad 1 \quad 2 \quad 3 \quad 0 \quad 1 \ldots
\]

\[
0 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6 \quad 7 \quad 0 \quad 1 \ldots
\]

Figure 7. DTDMA frame format

2) Packet Format

There are two modes of operation for the nodes in the network – transmit mode and control mode.

In transmit mode, the data packet (DATA) contains information about the frame length, slots assigned to the sender, maximum frame length of the sender and its neighbors and the data. In control mode, a new node uses the request packet (REQ) to request information on frame length and assigned slots to the nodes in its contention area. This control packet is always sent in slot 0 which is dedicated to request purposes only. Another packet used in control mode is the information packet (INF). This packet is sent by neighbors in response to the REQ packet of a new node. By sending this packet the neighbors indicate transition from transmit mode to control mode.

3) MPR-aware Dynamic TDMA Slot Allocation

The slot assignment in this protocol follows a completely distributed approach. The slot assignment process follows four steps.

In the first step, as a new node enters the network it sends a control packet in slot 0. In order to synchronize itself it listens to the DATA packets from the neighboring nodes. It learns the position of the first slot in a frame and the maximum frame length among all nodes in its contention area. It then sends REQ in the first slot of the next frame. Upon receiving the REQ packet all the neighboring nodes transition to control mode. All the neighbors then transmit INF packet in their assigned slots. This INF packet implies that the neighbor has transited to control mode.

In the second step, the new node upon receiving the INF packets from all the neighbors sets its frame length to the maximum frame length among all the nodes in its contention area. To do that, the new node has to merge the information from all INF packets: to learn the slot assignment:

- If the frame length of the new node is same as a neighbor, then copy the slot assignment information of that neighbor into the new frame.
- If the frame length is different i.e. S(0) = β S(i), where S(0) is the new node’s frame length, S(i) is the neighbor frame length and β is a integer of power of 2, then copy the information from neighbor node into every S(0)/β slots from the start in the new node’s frame.

This process is illustrated in Figure 8.
In the third step, the new node selects a slot using the following procedures:

- Getting an unassigned slot. After merging the information the new node looks for any unassigned slots. If any unassigned slot is found then it allocates that slot to itself. In case of multiple unassigned slots it allocates the minimum index free slot.

- Releasing multiple assigned slots. If there are no unassigned slots left we check for nodes with multiple assigned slots. If there is a node with multiple assigned slots then one such slot is freed and allocated to the new node. If more than one node has multiple assigned slots then the slot is released by the node with lowest index free slot and allocated to new node. This is illustrated in Figure 9. In this case node A and node B have multiple assigned slots i.e. node A has been assigned slot 1 and slot 5 whereas node B has been assigned slot 2 and slot 6. So the multiple assigned slot with lowest index i.e. slot 5 is freed from node A and assigned to the new node.

![Figure 9. Removing multiple assigned slots](image)

- Doubling the frame. If there are no unassigned and multiple assigned slots then the frame length is doubled and slot assignment is copied and merged using the technique mentioned in the previous section. This is illustrated in Figure 10. After doubling the frame and merging there is an unassigned slot 8. It corresponds to slot 0 in the original frame which is reserved for control packets but now free in the doubled frame length.

![Figure 10. Doubling the frame and merging](image)

As the last step of slot allocation, the new node sends an INF packet to all the neighbors and all neighbors update their slot assignment information accordingly.

![Figure 8. Merging information from different frames](image)

![Figure 10. Doubling the frame and merging](image)

Recall that OLSR is one of the most popular routing protocols in MANETs. OLSR uses MPRs (Multipoint Relays) to reduce the control overhead [13] [14] [15] [16]. In Inter-domain Routing scenario, when a domain runs on OLSR as its intra-domain routing protocol, the MPR nodes are usually located on the path that carries most of the intra-domain control messages. It is reasonable to include MPR information into Dynamic TDMA in Inter-domain routing scenario to further improve its performance. MPR awareness is added as an optional module to the dynamic TDMA and will affect its functionality in a minimal way by modifying its scheduling to include MPRs of a node. Adding it as an optional TDMA component has the benefit that any protocol, not only OLSR can use it.

The basic reasoning behind MPR aware TDMA protocol is that in OLSR an MPR node can forward traffic from all other nodes that have selected it as MPR. But in the original dynamic TDMA protocol his privilege in general is not considered. The MPR node is allocated slots just as any other node. In order to correct this, we make the protocol MPR aware so that any node which is acting as an MPR is given more slots in the frame to allow it sufficient slots to forward the traffic from other nodes. This is quite a reasonable choice to make.

The next important question is how many slots to allocate to an MPR node in the frame. This is answered by the MPR Selector (MPRS) set. MPRS is a set of nodes which have selected a particular node in question as its MPR. So, an MPR node will forward its own data as well as the data from all the nodes in its MPRS set. The number of MPR selectors for each MPR node should become an important consideration. The node which carries the most MPR selectors which means this node takes in charge of higher forwarding traffic, should be allocated more Dynamic TDMA slots.

The number of slots the MPR node X obtains, Slots(X), during the entire simulation will be approximately proportional to its MPR selector set as shown in (2).

\[
\frac{\text{MPR Node Slots(X)}}{\text{Total num of slots in entire TDMA domain}} = \frac{\text{Num of MPRS}}{\text{Total num of MPRS}}
\]

We increase the number of slots for MPR nodes by sending multiple insert node queries. This is a cross layer design solution because OLSR protocol maintains a data structure for all nodes that contains information about MPR Selectors (MPRS). So, we exchange this information with the MAC layer to enable MPR aware TDMA. The protocol starts as a general TDMA but after a certain predefined time (the time it takes for the MPRS table creation at the routing layer) the protocol schedule is modified to include MPR awareness. This gives a better performance to the OLSR routing protocol. The MPR-aware Dynamic TDMA slot allocation scheme is invoked periodically to adapt the dynamic network topology for MANETs.

B. MPR-aware gateway election in Inter-Domain Routing

The gateway node selection algorithm in an inter-domain routing scenario is very crucial [17] [18]. A careful selection of the gateway node ensures efficiency and accuracy of inter-domain communications. As introduced in our previous paper [2] [3], the gateway node is selected based on the neighbor ratio (i.e. number of neighbors to the total number of nodes in all the related domains) and the neighboring node distribution in the related domains is calculated based on the Jain’s index. The neighbor ratio represents the transmission efficiency and the node distribution represents the balance of node distribution among various domains. The index can be represented mathematically as (3) and (4).

\[
B(\text{balance index}) = \frac{(\sum x_i)^2}{n \times \sum x_i^2}
\]

\[
R = \frac{n}{N}
\]

Here, \( n \) is the total number of domains; \( x_i \) is the ratio of the number of neighbors to the number of members in domain \( i \).

Here, \( R \) is the neighbor ratio (represents transmission efficiency); \( N \) is the number of nodes in all the related domains, \( n \) is the total number of neighbors in all the domains.
Similar concept can be used in our case of MPR aware gateway election. If a subdomain works on OLSR routing protocol, the nodes that act as MPRs should be more likely to become gateways among the gateway candidates. The more MPR Selectors (MPRS) an MPR node has, a better opportunity to become a gateway node. We define the weight of an MPR node as the ratio of the number of its MPR Selectors vs. the total number of MPR Selects in its domain (assuming it runs OLSR), as shown in (5).

\[ W = \frac{\text{num of MPRS}}{\text{total num of MPRS}} \]  

(5)

This weight factor is zero for the nodes that do not run OLSR. In domains operating with different routing and MAC protocols, Gateway node is selected considering both transmission efficiency and node distribution balance (6).

\[ \text{Gateway} = \text{Max}[\alpha \times W + \beta \times B + \gamma \times R] \]  

(6)

Here \( \alpha, \beta, \gamma \) (set in our example as 0.2, 0.5 and 0.3) are parameters that are determined by the simulation result based on specific scenario and network conditions and their sum is 1. The gateway node is selected such that it maximizes the function in (6). In inter-domain routing scenario, the gateway selection should consider both topology connections and efficiency/balance. Namely, not only the number of gateway’s neighbors is a determinant fact, but also its connection with neighbors and even domain coverage. We value not only the packet delivery ratio but also the traffic throughput. Thus, an MPR node running OLSR protocol is a more desirable Gateway candidate as it will acts as intersection of OLSR traffic.

IV. IMPLEMENTATION AND EVALUATION

We have implemented MPR-aware IDR under Qualnet network simulator 5.0.2. Network data traffic is generated by CBR sources. Packet size is 512 bytes. The source-destination pairs are randomly selected. The dimension of the network scenario is 2000m×2000m. Different seeds are used in the simulations.

The mobility model is RPGM [19]. Each node in a domain has a common group motion component. In addition, each node has an individual intra-group motion component. In our simulation the group speed varies under different scenarios, while the intra-group speed is fixed in the range of [0-5 m/s] and the pause time is 10 seconds. Total simulation time is 900 seconds.

A. Comparison between STDMA and DTDMA

In this section, PHY/MAC protocol is TDMA. The routing protocol is OLSR-INRIA.

In order to compare the performance of distributed DTDMA vs. STDMA, we measure the Receiver Throughput under: 1) different traffic due to varying packet intervals at the sender side, and; 2) different node density.

In Figure 11, the number of nodes is fixed while packet interval changes. 16 nodes are randomly distributed in a test scenario of dimension 2000m×2000m. Packet interval is initially 0.01s, and then gradually increased to 0.5s. Because traffic = packet size / packet interval where packet size is 512 bytes, network traffic is initially 409.6 kbps, then gradually decreased to 8.192 kbps. 50 points are used to plot each curve.

At the very beginning, the two curves are very close to each other, and average receiver throughput in both STDMA and DTDMA scenarios grows. When network traffic reaches 22.755 kbps, throughput in STDMA network flattens out at 23.549 kbps, while it keeps growing in DTDMA network. DTDMA maximum throughput shoots up to 126.737 kbps, 5 times that of STDMA. This maximum throughput is reasonable in the given 2M-link-capacity and 16-node scenario. From this figure, we can also safely conclude that DTDMA has a much better performance than STDMA.

Figure 11. Average receiver throughput under different TDMA implementations

In Figure 12, the packet interval is fixed (0.02s) while the number of nodes changes. The number of nodes is initially 10, then gradually increased to 80. 8 points are used to plot each curve.

Figure 12. Average receiver throughput under various node densities

<table>
<thead>
<tr>
<th>Number of Nodes</th>
<th>20</th>
<th>40</th>
<th>60</th>
<th>80</th>
</tr>
</thead>
<tbody>
<tr>
<td>Throughput in STDMA network (kbps)</td>
<td>66.164</td>
<td>34.251</td>
<td>11.103</td>
<td>3.374</td>
</tr>
<tr>
<td>Throughput in DTDMA network (kbps)</td>
<td>18.130</td>
<td>4.785</td>
<td>2.399</td>
<td>1.625</td>
</tr>
<tr>
<td>Difference (kbps)</td>
<td>47.854</td>
<td>29.376</td>
<td>8.704</td>
<td>1.749</td>
</tr>
</tbody>
</table>

Table 1. Average receiver throughput with 20, 40, 60, 80 nodes

In Figure 12 and Table 1, as the node density increases, the throughput in both networks drop, and so does its difference
between DTDMA and STDMA (from 61.346 kbps under 10 nodes, to 1.749 kbps under 80 nodes). The reason is that in STDMA network, the number of slots in a single frame is simply the total number of nodes in the network; in DTDMA network, the number of slots depends on the size of a node’s contention area. As the node density increases, sizes of contention areas increase. As a result, in both cases, the slot number in a single frame increases, so the probability of each node transmitting its own data decreases. Consequently, average throughput at the receiver side drops.

B. Evaluation of MPR-aware Gateway Election in IDR

Two subdomains in the experiments under this section are partially overlapped.

The PHY/MAC protocols of the two non-overlapped parts are CSMA/CA with RTS/CTS, and TDMA, respectively. Nodes in the overlapped part run both MAC protocols on multiple interfaces. All nodes run our improved IDR protocol in this paper. Specifically, nodes in TDMA domain also run OLSR-INRIA, while those in CSMA domain also run AODV.

In order to compare with the original IDR, one of the commonly used metrics of evaluating routing protocols for wireless ad hoc networks is considered – normalized control overhead: the ratio of total number of control packets to total number of CBR bytes sent during the entire simulation time.

Experiments have shown that average receiver throughput increases as network traffic grows. However DTDMA throughput is much better and saturates later than STDMA. Another important observation is that as node density increases, both DTDMA and STDMA throughput drops, and the difference in throughput between the two schemes decreases. To put it another way, high node density degrades throughput performance in both networks.

We also have studied the advantage of OLSR routing and have implemented an MPR-aware gateway election for inter-domain routing. The new IDR gateway election algorithm takes both transmission efficiency and node distribution into consideration. It reduces the control overhead and improves the performance of the original routing protocol. We plan to do more research about the mobility aspects, especially regarding node joins and leaves. Likewise, we plan to test other routing metrics in the future, including hop distance.

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V. CONCLUSION AND FUTURE WORK

In this paper, we proposed a new MPR-aware Dynamic TDMA Protocol and MPR-aware Inter-domain routing gateway election algorithm. We implemented in Qualnet a distributed DTDMA MAC protocol which takes contention area and neighbor list into consideration in slot assignment, and also add MPR information to further optimize the slot allocation algorithm.