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Scheduled Channel Access Using Geographical Classification

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Abstract—**Geographical Classification Multiple Access (GCMA) is introduced for scheduled channel access in large wireless networks. GCMA uses the geo-spatial coordinates of nodes, together with their transmission and interference ranges, to define collision-free transmission schedules using deterministic distributed algorithms. These algorithms require each node to know only the geo-spatial coordinates of its immediate neighbors to derive correct transmission schedules, even in the presence of hidden terminals. The transmission frames in GCMA consist of the minimum number of time slots needed to avoid multiple access interference, given the transmission and interference ranges of the nodes. GCMA is compared against representative examples of alternative approaches to medium access control; the results of the simulation experiments show that GCMA attains higher packet-delivery ratio and better goodput with end-to-end delay comparable to the other protocols.**

I. INTRODUCTION

Many medium access control (MAC) protocols have been proposed and implemented for wireless networks with the main objective of improving the throughput and transmission delays experienced by nodes in the presence of multiple access interference (MAI). As Section II summarizes, most prior MAC protocols are based on contention, scheduling, or reservation schemes, and all these approaches select transmission times for nodes in a way that is inherently independent of the spatial connectivity among nodes. Furthermore, the few MAC protocols proposed in the past that take advantage of geo-location information are limited to one-dimensional settings or are impractical for mobile networks.

This paper presents GCMA (Geographical Classification Multiple Access), a novel approach for the sharing of multiple access channels in wireless networks with or without hidden terminals that takes advantage of knowing the transmission and interference ranges of a node, as well as the geographical coordinates of a node and its immediate neighbors. Section III describes GCMA, which to the best of our knowledge is the first approach to fully exploit the inherent ordering of a geographic coordinate system to establish collision-free transmission schedules in wireless ad-hoc networks.

GCMA assumes a geographical origin for a network, and organizes the Euclidean space into fixed-size square regions consisting of c square cells ordered according to geographical location. The length of each square edge is smaller than the transmission range assumed for a node, so that all nodes in the same cell can hear one another. The number of cells in a region is defined by the transmission and interference ranges assumed for the nodes, such that no two nodes in the same or different square regions can interfere with each other when they transmit concurrently. The length of a transmission frame in GCMA is based solely on the minimum number of time slots required to address MAI, given the transmission and interference ranges assumed for all nodes.

Section IV compares the performance of GCMA in terms of packet-delivery ratio, average end-to-end delay and goodput ratio against the performance of representatives of contention (IEEE 802.11 DCF [9]), reservations (Five Phase Reservation Protocol [27]), and elections (Node Activation Multiple Access [2]). The results of our simulation experiments indicate that GCMA is a more efficient alternative than contention, reservations and topology-dependent transmission scheduling, in terms of all performance metrics.

II. RELATED WORK

Many MAC protocols have been proposed to control access to a common wireless channel using contention schemes that attempt to eliminate collisions due to MAI (e.g., MACA [17], FAMA [11], RIMA [12], IEEE 802.11 [9]). While these protocols succeed to some extent, their performance degrades at high loads because they are unaware of which nodes are attempting to transmit and must simply react to the effects of MAI perceived in the channel.

The MAC protocols based on transmission-scheduling or reservation schemes designed to date assume that the channel is divided into transmission frames with a number of slots being somehow related to the number of nodes in the network or the density of the network. Transmission-scheduling schemes that are independent of the network topology establish schedules in which the times when a node is allowed to transmit in a frame correspond to a unique code, such that the node is ensured to have at least one time slot during which no interfering node can also transmit (e.g., [7]). Unfortunately, this independence from network topology comes at a very high performance cost. In fact, Kunz and Rentel [20] have shown that this approach has similar performance to that of slotted ALOHA.

Topology-dependent transmission scheduling protocols attempt to establish transmission schedules taking into account the connectivity of the network and in some cases the traffic at each node. The assignment of time slots to nodes is based either on the election of entities competing for the data time slots (nodes or links), or the selection of reservation requests for data time slots according to a set of predefined rules. Some schemes require an initial topology-independent schedule, followed by some negotiation among network nodes used to obtain a final schedule (e.g.,[8], [10], [25]). In topology-dependent scheduling protocols based on reservations (e.g., CATA [22], FPRP [27]), the channel is divided into frames consisting of a fixed number of time slots, and each time slot is divided into several mini-slots dedicated for the contention and reservation of the time slots as well as the transmission of data in the time slot. In FPRP, the frame size for each node in the network is set based on network heuristics and nodes use reservation requests to reserve slots in the frame. There are many examples of topology-dependent schemes based on the election of transmission schedules in a distributed manner. To elect transmission schedules, each node knows the identities of all other nodes one and two hops away from itself, and the present time in the network (e.g., [2], [3]). Nodes use a contention-based approach during the control section of a frame to communicate to their neighbors either the identifiers of their own neighbors and themselves, or the identifiers of the links to their own neighbors. Each node builds and maintains a list of contending entities (nodes or links) and uses this list to determine which node should be given access to the channel during each time slot of the data section of the frame. To accomplish this task, the node applies a permutation function on the list of contending entities to select a winning node from the list of nodes for each time slot of the transmission frame.

The main limitation of topology-dependent MAC protocols based on elections or reservations is that the time taken for all nodes to access the channel at least once or the jitter of consecutive channel accesses by the same node may become very large when the number of nodes in the two-hop neighborhood increase.

Considerable work has been reported on the establishment of efficient transmission schedules in a distributed manner taking into account the nodal traffic demands and attempting to limit the overhead incurred in the establishment of schedules that approach the optimum [5], [16]. However, none of the approaches reported to date are practical in wireless networks because of the extensive signaling they incur.

There have been many routing protocols that take advantage of location information [13]; however, only a few MAC protocols have been reported that use geographical locations to help determine which nodes should access the channel. Many of these MAC protocols were designed for one-dimensional vehicular networks (e.g., [1], [4], [18], [23]); and only limited work exists on using geographical location to help define how nodes should share a common channel.

Zhang and Haenggi [26] proposed location-based MAC (LMAC). LMAC organized the plane into a square lattice and defines transmission areas (TA) at the center of the vertices of such a lattice. Nodes move and are allowed to transmit using an ALOHA-like scheme when they are in any of the TAs.

Wu and Bao [24] proposed GAALS (Grid-Based Channel Resource Allocation and Access Scheduling Using Latin Squares) for wireless mesh networks in which each node knows its location and the location of its neighbors and accesses multiple channels. GAALS uses location information to assign channels to cells, and relies on nodes exchanging one-hop neighbor information to address MAI within a cell. However, GAALS does not handle mobility of nodes between the grids and contention among multiple nodes within the same grid.

From the above summary, it is apparent that the vast majority of prior approaches on MAC attempt to assign channel access time to nodes based on either fixed assignments (TDMA), contention, reservations, or transmission scheduling, and that very limited prior effort has addressed the use of geographic location information to improve the efficiency of channel access.

III. GCMA

It is assumed that: (a) the radios used in the network are half-duplex and can tune to only one channel at a time; (b) radio links are bidirectional, which means that the transmission and receiving ranges of nodes are the same; (c) time is slotted with time slots having a fixed duration, and any pair of nodes can be synchronized at the time-slot level; and (d) each node is endowed with a GPS receiver and knows its geographical location, but it does not know the terrain dimensions in which the network operates. For simplicity, the rest of the paper also assumes that all the nodes have the same constant transmission, receiving and interference ranges; and that the network uses a single channel. However, GCMA can be applied to far more general cases with multiple channels.

A. Spatial Classification of Nodes and Channel Structure

The latitude and longitude coordinates of the geographical location of a node are available as 'x' and 'y' coordinates in the two-dimensional Euclidean space starting from a common point of origin (e.g., the north pole). As Fig. 1 shows, the Euclidean plane is organized into square blocks starting from the point of origin, with the length of the edge of a block being D. Each block is divided into $m = n^2$ equal cells of edge length d_c, and each cell is assigned a location number from 1 to n^2 according to its position in the block.

The length of D is set to be $D \geq (d_c + d_t + d_i)$, where d_i is the maximum interference range and d_t is the maximum transmission range for the network nodes. This is done to ensure that no two nodes that are located in different adjacent blocks but in cells with the same location numbers interfere with each other when they transmit concurrently. For example, even though nodes A and C in Fig. 1 are located at the borders of their respective cells with location number 1, no receiver for node A can experience interference from node C.

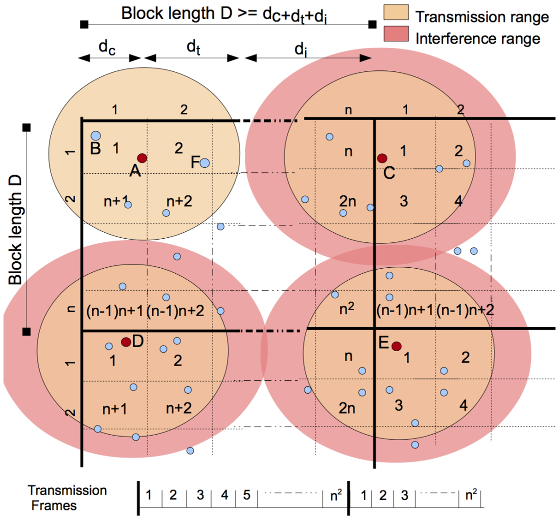


Fig. 1. Spatial Classification into n cells and channel structure

To ensure that all nodes in the same cell can hear one another, d_c must be such that $d_c = \frac{D}{n} \leq d_t/\sqrt{2}$. This is because cells are squares and hence the two farthest away nodes within the same cell must be at the vertices of one of the two diagonals of the cell with edge length d_c.

As Fig. 1 also shows, the common channel is organized into transmission frames, with a transmission frame F_t consisting of a constant number of time slots equal to the number of cells in a block (n^2).

Each time slot in GCMA is used for the transmission of a *Hello* and zero or more data packets. A *Hello* consists of the node identifier (ID) and its own geographical coordinates. Each node maintains a list of one-hop neighbors along with the geographical coordinates reported by each neighbor. The node also has a counter that is used to keep track of number of active one-hop neighbors that belong to the same cell as the node itself. The counter is incremented every time a *Hello* is received from a new neighbor in the same cell and it is decremented when a neighbor fails to send a *Hello* for a preset period of time. This value gives the number of one-hop neighbors of a node located in the same cell as the node itself. For example, in the example shown in Fig. 1, over time, node F learns that it is the only active node in its cell, while node A may learn that a second node B is present in its cell. Clearly, a node hears all the transmissions within its receiving range, which has length d_t according to our assumptions.

B. Transmission Scheduling

Once the node detects its geographical location, its block and cell in the block are defined automatically. Furthermore, since each cell number is assigned a time slot in each transmission frame F_t, each node also knows the time slot number where itself and all other nodes in its cell can transmit. Let k_x and k_y be the cartesian coordinates x and y of a node k. The values of $\frac{k_x}{d_c}\%n$ and $\frac{k_y}{d_c}\%n$ are then calculated and mapped to the corresponding cell number.

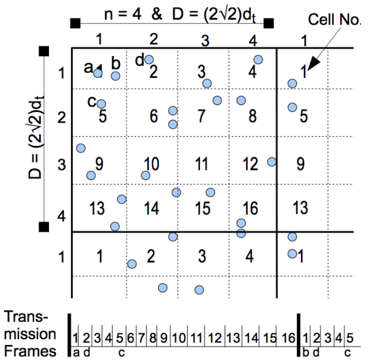


Fig. 2. Spatial classification for n=4 cells and $d_t == d_i$

Algorithm 1 Transmission Algorithm

```
Let $List_i$ be a sorted list at node $i$ and $count = 0$
Insert $i$ in $List_i$
Let $OHN_i$ denote one-hop-neighborhood of node $i$.
for all k in $OHN_i$ do
    Calculate $\frac{k_x}{d_c}\%n$ and $\frac{k_y}{d_c}\%n$ to find cell $c_k$
    if $c_k == c_i$ then
        Insert $k$ in sorted list $List_i$
        $count++$
    end if
end for
Find index $j$ of node $i$ in $List_i$
Slot cell $c_s = Time.slot.num\%n^2 + 1$
if $c_s == c_k$ then
    if $\frac{(Time.slot.num - c_s)}{n^2}\%count == j$ then
        $State_i \leftarrow Transmit$
    else
        $State_i \leftarrow Receive$
    end if
else
    $State_i \leftarrow Receive$
end if
```

For simplicity, in the rest of this paper, we assume that $d_t = d_i$, which is the same assumption made for previous MAC protocols. This leads to the spatial classification and channel structure shown in Fig. 2, where blocks have edges of length $D = 2\sqrt{2} \times d_t$. It can be show that a block must then consist of 4×4 cells, with cells numbered from 1 to 16.

Algorithm 1 is used to determine the rate at which a node accesses the time slots t assigned to the cell in which the node is located. If a node detects that it belongs to cell c and that it is the only node in the cell in its neighborhood, then the node transmits in all the slots at which $Time\text{-}slot\text{-}number\%m == c$ or if $c == m$, $Time\text{-}slot\text{-}number\%m == 0$, where $m = n^2$. Therefore, in Fig. 2, node c is the only node that is located in cell number 5 and transmits in slots $5, 21, 37, 53, ...$, and so on.

Consider the case when there are two or more nodes in the same cell within a block. Each of these nodes must take turns to access the channel in the slot assigned for their cell in alphanumeric order. As shown in Algorithm 1, the *count* value (number of neighbors in the same cell) is used in order

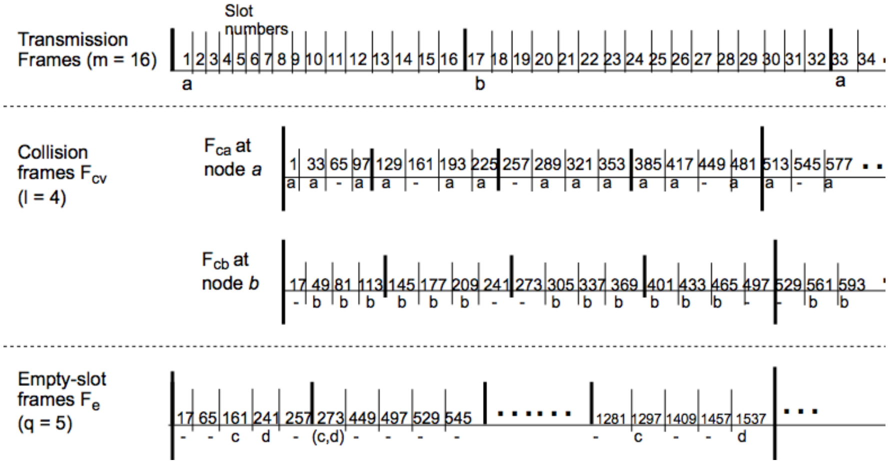


Fig. 3. Frame structure for the spatial classification of $n = 4$ cells in Fig. 2

to determine the schedule at each node.

C. Network Joining and Mobility Handling

The method used to handle mobility and joining of new nodes is similar in principle to the topology-transparent scheduling algorithm based on the evaluation of polynomials over a Galois field as proposed by Chlamtac and Farago [6].

In addition to having frames of size m slots in order to divide nodes into groups for transmission as explained in the previous section, there are two more frame structures used for detecting collisions and handing mobility in the network. The frame structures used in GCMA are shown in Fig. 3.

At the top-level is the transmission frames of size $m = n^2$ slots corresponding to the number of cells within a block in the network. Each node belongs to a specific cell and hence can attempt to transmit in only one of the m slots during each frame. All the slots during which a node v is scheduled to transmit as per Algorithm 1 form the *collision frames* f_{cv}. Collision frames f_{ca} and f_{cb} for nodes a and b in Fig. 2 is shown in 3. A collision frame f_{cv} of node v is seen as a set of l slots: $\{s_0, s_1, ..., s_{l-1}\}$ and l such collision frames f_{cv} form a *collision super frame* for node v, F_{cv}, of size l^2.

We define the *empty-slots set* as the set of time slots $S_e \in F_{cv}$ that a node wins according to the transmission algorithm but the node chooses to leave empty (without a transmission), thereby leaving it available for new nodes in the neighborhood to send their $Hellos$. The empty slots also enable nodes to detect collisions when two nodes fail to hear the $Hellos$ of each other and transmit in the same slot. The slots that are left empty by a particular node is determined by the position within the cell that the node is currently located at.

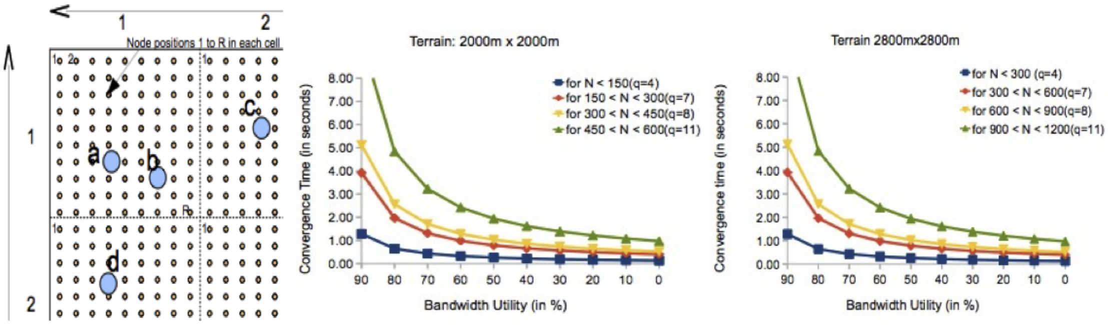
Let $GF(l)$ be a Galois field of order l, where $l = s^m$, s is a prime and $m \geq 1 \in Z^+$ is an arbitrary positive integer. Every element in $GF(l)$ is labeled with the integers $0, 1, ...l-1$. Every node position r of R possible node positions in a cell is assigned vector-identifier polynomials $VID_r[x]$ of degree k with coefficients in $GF(l)$ such that at least one of the polynomials assigned is unique for the node. The number of polynomials assigned p depends on the rate of empty slots required to efficiently handle mobility for the network. Each node v uses the polynomials VID_r of the position r in the cell that it currently occupies. The positions within a cell are shown in Fig. 4(a).

Let the collision super frame size be $l' = l^2$ slots. The set of time slots $S_{ev} \in F_{cv}$ during which node v refrains from transmitting even though is entitled to the time slots is determined according to Algorithm 2.

Algorithm 2 Empty Slot Algorithm

```
Let $p$ be the number of polynomials assigned
for Each node $v$ in the cell at position $r$ do
    for ($i = 0 : l - 1$) do
        for ($j = 1 : p$) do
            $s_{ev} = il + VID_{rj}[i]$
            $S_{ev} = S_{ev} \cup s_{ev}$
        end for
    end for
end for
```

In Algorithm 2, each polynomial is evaluated for every value between 0 and $l-1$ and assigned to the empty slot assignment set S_{ev} at each node v. The frame of size l^2 can be visualized as composed of l subframes with l slots each and there are p empty slot within each of the subframes. Fig. 3 shows the collision frames with one empty slot per frame ($p = 1$) . In order to guarantee that there is at least one empty slot in S_e in the super frame of l^2 slots, which is unique to a node v, the two constraints that must be satisfied are: (a) $l^{k+1} \geq R$; and (b) $l \geq kP_{max} + 1$, where P_{max} is the maximum number of nodes within a square cell of size $d_c \times d_c$, and R is the number of possible node locations within such a cell as shown in Fig. 4-(a). The first constraint makes sure that every location within a cell has a unique code. The second constraint guarantees that there is at least one empty slot that is not common for any two nodes (see [6] for the proof), thereby allowing nodes to detect any clash of schedules.



(a) Positions in cell (b) Convergence time for 2000x2000m n/w (c) Convergence time for 2800x2800m n/w

Fig. 4.

Let $l_1, l_2, ...$ be the sequence of increasing powers of primes (i.e, $2, 3, 4, 5, 7...$), then Algorithm 3 is used to select the l value for a network.

Algorithm 3 Algorithm to set values of l

```
i=0; k=0;
while $k < 1$ and $l^{k+1} < R$ do
    $i = i + 1$; $l = l_i$;
    $k = \lfloor \frac{(l-1)}{P_{max}} \rfloor$
end while
```

The aggregate of the empty slots S_p of all nodes within a cell form the third frame structure called the empty-slot frames f_e, each of size q. The set of f_e such empty-slot frames together form the empty-slot super frame F_e of size q^2 as shown in Fig. 3. Unlike the collision frames F_{cv} that are unique to each node, the empty-slot frames F_e are unique to each cell within a block.

When a new node joins a network or when a node enters a new cell, it transmits its $Hello$ in q empty slots before it executes the transmission algorithm and starts transmitting data packets. The node choses one empty slot in each of the q empty-slot frames f_e to transmit a $Hello$. Algorithm 4 determines the set of slots $S_t \in F_e$ at which the new node v transmits $Hellos$.

Algorithm 4 New Node Algorithm

```
At new node $v$ at position $r$ in the cell,
$S_t(0 : q - 1) = 0$; //Initializing $q$ slots
for $(i = 0 : q - 1)$ do
    $S_t(i) = iq + VID_r[i]$
end for
```

To guarantee that there is at least one slot in S_t in the super frame of q^2 slots that is unique to a node v, two constraints must be met: (a) $q^{r+1} \geq R$; and (b) $q \geq rP_{max} + 1$, where P_{max} is the maximum number of nodes in one cell, i.e., the maximum number of nodes within a square cell of size $d_c \times d_c$, and R is the number of possible node locations within such a cell as shown in Fig. 4-(a). The algorithm to select the q value for a network is the same as Algorithm 3 used to select the l value. Algorithms 4 and 2 can be seen as inverses, wherein while Algorithm 2 is used to leave a slot empty every l slots, Algorithm 4 is used by new nodes to transmit once every q slots. For example, in Fig. 3, when nodes c and d enter cell 1, they chose one slot in every empty-slot frame f_e, based on the position within the cell they are located, to transmit their $Hellos$. It has been shown in [6] that each node within the cell is guaranteed to transmit at least one collision-free $Hello$ within q^2 empty slots, thereby securing a collision free transmission schedule.

The number of available node positions within a cell used to generate the unique vector-identifier polynomials affects the time taken by nodes to obtain a schedule since the value of q depends on the value of R. By using the node positions to generate the polynomials, the cell size can be varied to obtain the desired values of R and q for the network. Alternatively, node IDs of nodes can be used to generate the unique polynomials. In this case, the value of q is such that $q^{r+1} \geq N$, where N is the number of nodes in the network. Such a scheme would be suitable for networks in which the total number of nodes is less than the number of positions R within a cell (like the networks used for simulation in Section IV). The average rate of empty slots for a cell determines the time taken by nodes to converge to a schedule when new nodes join the network and when nodes move from one cell to another. Therefore, a tradeoff exists between the average bandwidth utility at each node and the schedule convergence time for nodes within a cell. Figures 4-(b) and 4-(c) show the bandwidth utility and the corresponding average convergence times for uniformly distributed networks of dimensions 2000x2000m and 2800x2800m respectively. The nodes have a transmission range of 250m and the cells are of length 170m with slot duration of 0.5ms. The results show that GCMA incurs small convergence times of just a few seconds while supporting a large bandwidth utility even for large numbers of nodes.

IV. PERFORMANCE COMPARISON

We compare GCMA with IEEE 802.11 DCF, NAMA, and FPRP assuming the 802.11b physical layer with a data rate of 11Mbps, given that the Qualnet simulator currently does not support the 802.11n physical layer. AODV is used as the routing protocol, given that it is representative of the signaling incurred in routing schemes [15]. We use packet delivery ratio, average end-to-end delay and the application goodput as our performance metrics. The simulation was done for two different terrain dimensions in order to study the performance of the protocols for different node densities, neighborhood sizes, and number of collision domains. The nodes have a transmission range of around 250m. We use a combination of random waypoint and group mobility models as our mobility model. The members of a group move following the group mobility model, whereas nodes inside the group move according to the random waypoint mobility model within the group area. The pause time is set to 10s and the minimum and maximum velocities are set to 1 and 5 m/s with a total of 5 groups. This mobility model attempts to depict common situations in which a few members of the same team tend to move together.

We used the discrete event simulator Qualnet [19] version 4.5,which provides a realistic simulation of the physical layer, and a well-tuned version of IEEE802.11 DCF. Each simulation was run for randomly distributed 100 node networks for ten different seed values. The time-slot duration for NAMA, FPRP and GCMA was set to 1ms, with the protocols capable of transmitting multiple data and control packets during a single time slot. The *Hellos* are sent for both NAMA and FPRP at intervals of 500 milliseconds.

To study packet-delivery ratio, the simulation was run for an increasing number of flows for 150s, with no packets being generated after 100s in order to allow for the maximum packets to get delivered with each protocol. Each flow generates 10 packets per second, with each packet consisting of 512B, and each flow has an average of four hops to destination in the 2400m x 2400m network and eight hops in the 3200 x 3200 network. It can be seen from Fig. 5(a) that GCMA performs much better than all the other protocols as the number of flows increases.

To study end-to-end delays while avoiding any bias due to different number of packets delivered for the different protocols, the number of flows was varied from 1 to 50 with each flow generating 1 packet per second. This results in a similar packet delivery ratio for all protocols, thereby making the comparison of average end-to-end delay for the different protocols fair. It can be seen from Fig. 5(b) that GCMA attains smaller end-to-end delays than NAMA and FPRP, which is due to the deterministic way in which slots are assigned to nodes using their coordinates. It can also be observed that 802.11b offers less delay than GCMA when there are fewer flows, which is the result of relay nodes having to wait for their transmission turn and the lack of scheduling coordination among relays. However, the delays in GCMA are always below 300 ms and 802.11 incurs higher delays than GCMA as flow load increases.

The two goodputs shown in Fig. 5(c) and Fig. 5(d) for the two terrain dimensions are: (a) the ratio of data packets received over the data packets sent; and (b) the ratio of data packets received over the total number of packets sent, which consists of all data packets sent, the routing control packets sent, and the MAC control packets sent. The first measure of goodput (Fig. 5(c)) is used to show the number of data packets lost for each protocol due to interference. It is clear from the results that GCMA and NAMA avoid collisions, and that 802.11 and FPRP do experience packet collisions, which can be attributed to the interaction between signaling packets and data packets. The second measure of goodput (Fig. 5(d)) shows the goodput achieved when all the control overhead is taken into account. When a single flow is present, 802.11b has better goodput than GCMA, because the control packets generated are proportional to the traffic load, while all nodes generate MAC control packets in GCMA. For more than one flow, GCMA outperforms the other protocols. The importance of collision-free scheduling is very clear for 10 of more flows.

V. CONCLUSION

We introduced GCMA, a novel approach to transmission scheduling for medium access control in wireless networks based solely on deterministic algorithms operating using the geographical coordinates of a node and those of its immediate neighbors. An advantage of GCMA over traditional transmission-scheduling schemes is that the channel can be organized into fixed-length transmission frames of the minimum length needed to combat MAI, independently of the network size, shape, density, or node degree. This eliminates design decisions that may impact performance negatively. Because the location information needed in GCMA has to be only as granular as needed by the transmission range of communicating nodes, each node can be informed of its geographical location in a number of ways. GPS can be used for the case of mobile networks, or location information can be loaded into the device for the case of very simple nodes operating in static networks.

The deterministic nature of GCMA eliminates the large variances in channel access times that is common in many prior MAC protocols. Simulation experiments were used to illustrate that GCMA outperforms representative examples of traditional MAC protocols based on contention, reservations, and elections (IEEE 802.11, FPRP, and NAMA) in terms of packet-delivery ratio, goodput, and end-to-end delays.

GCMA opens up a new area of research on medium access control (MAC) for wireless networks by classifying nodes based on their geographical coordinates. Our future work addresses GCMA for the case of multiple channels, the integration of multiple transmission ranges, and the coordination of schedules among relaying nodes.

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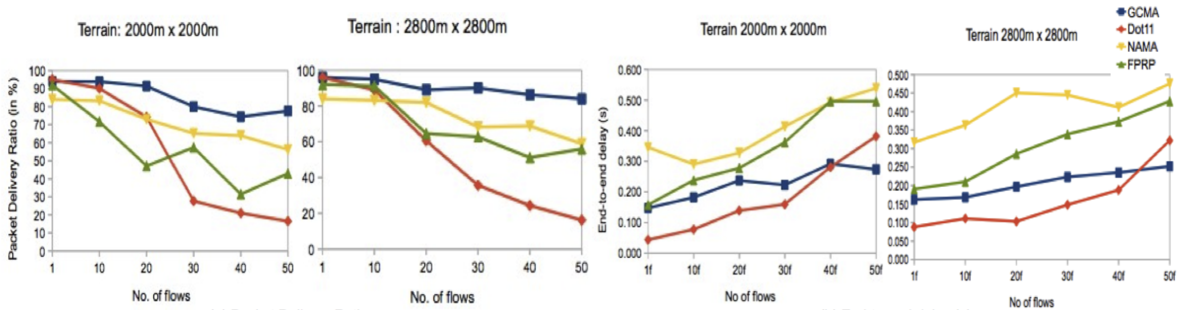
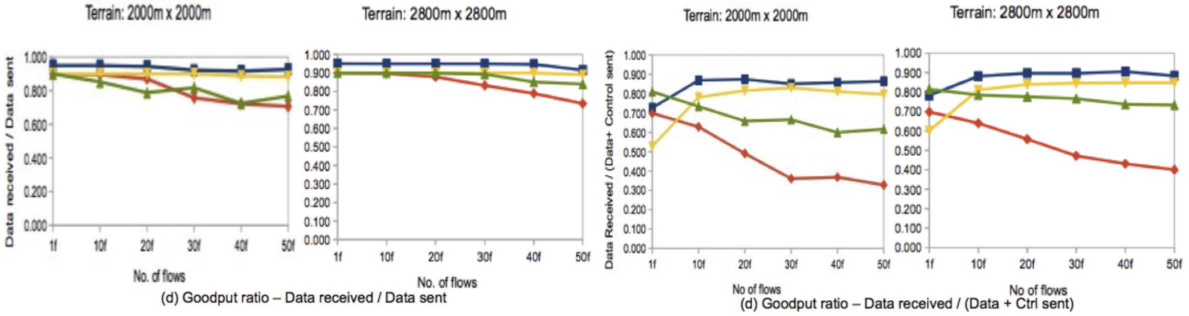


(a) Packet Delivery Ratio

(b) End-to-end delay (s)



(d) Goodput ratio – Data received / Data sent

(d) Goodput ratio – Data received / (Data + Ctrl sent)

Fig. 5. Simulation results

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