Space-Time Division Multiple Access (STDMA)* and Coordinated, Power-Aware MACA for Mobile Ad-Hoc Networks

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Abstract - **Space-Time Division Multiple Access (patent pending) is the first position-based TDMA scheduling protocol for mobile ad-hoc networks, and is the generalization of the cellular TDMA with spatial re-use bandwidth allocation paradigm that is encountered in cellular TDMA networks. In STDMA, space is divided into virtual geographic cells (space slots) that are grouped into periodically repeating virtual frames (space frames) in order to facilitate spatial re-use, and time slots are assigned to space slots. Each node is equipped with a means of determining its instantaneous location (i.e., GPS), and therefore always knows the identification of the space slot that contains it, and consequently the time slot that is assigned to it. In this paper, we show that STDMA is a topology-transparent scheduling protocol that guarantees a unique transmitter within a 2-hop neighborhood, and that the maximum number of time slots between successive transmissions by a given node (produced by STDMA) is linearly bounded by the maximum network degree, therefore exponentially outperforming currently proposed topology-transparent TDMA scheduling protocols. We then apply STDMA as the channel access scheme for the control channel of Coordinated MACA, a conflict-free TDMA link-activation protocol.**

I. INTRODUCTION

The problem of scheduling collision-free broadcasts by a node (also called node activation) to all its neighbors without any other packet interfering its transmission is critical in mobile ad-hoc networks. The problem has been formulated in such a way that only one node is assigned to a time slot within its two-hop neighborhood.

Collision-free scheduling of broadcast transmissions is critical in mobile ad-hoc networks, for two reasons:

a) MAC layer slot-reservation mini-packets (i.e., RTS/CTS) have to be sent in broadcast mode, in order to successfully coordinate collision-free {slot, code (or frequency)} pair assignments within a two-hop neighborhood, and
b) Network control/maintenance packets (i.e., hello packets, routing-table updates) are transmitted in broadcast mode for efficiency.

Currently proposed node activation algorithms can be broadly divided into two categories: topology-dependent (graph-based) and topology-transparent (code-based).

Topology-dependent (graph-based) scheduling algorithms ([1], [2], [3], [4], [5]) dynamically re-assign time slots, in a distributed manner, within a two-hop neighborhood in response to topology (connectivity) changes. The disadvantage of topology-dependent TDMA scheduling algorithms is that their efficiency and robustness is vulnerable in a highly mobile environment, since:

a) The TDMA schedule re-computation process may never converge if the rate of topology change exceeds the rate at which the protocol can re-compute and distribute the new schedules. Let D (network degree) denote the average number of 1-hop neighbors of any node in the network. Then, the average number of 2-hop neighbors of any node is proportional to D^2 (D neighbors, each having D neighbors). With topology-dependent scheduling, the TDMA transmission schedule has to be recomputed every time 2 previously non-neighboring nodes become 1-hop neighbors; since a new 1-hop neighbor can only be obtained from the set of 2-hop neighbors, the frequency of schedule re-computation for topology-dependent scheduling protocols is proportional to D^2, as well as the degree of mobility of the network. Therefore, for networks that are highly mobile and moderately dense the topology is highly volatile, resulting in an unstable TDMA transmission schedule for topology-dependent scheduling.
b) Significant overhead may be incurred in the process of coordinating time slot re-assignment between the nodes of a two-hop neighborhood, resulting in excessive consumption of precious bandwidth and battery-power resources.
c) Depending on the timing of events, the density of the network, and the particular connectivity, the time slot re-assignment process within a given 2-hop neighborhood may trigger time slot re-assignments in adjacent 2-hop neighborhoods, causing a time slot re-assignment 'ripple' effect that could potentially propagate a large distance away from the originating neighborhood.
d) Transmissions are lost during the transient period of time slot re-assignment. The higher the volatility of the network topology, the higher the number of lost transmissions. If the lost packets carry information that is necessary for network healing, or information pertaining to scheduling of point-to-point transmissions, then network performance can take a significant hit during those time slot re-assignment transient periods.
e) For most graph-based scheduling algorithms, the upper bound on the number of time slots between 2 consecutive transmissions by the same node is proportional to D^2.

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Therefore, the individual node broadcast throughput falls quadratically with respect to the network degree (D), resulting in sharp performance degradation for moderately to heavily dense networks.

In order to overcome the above deficiencies, a number of topology-transparent (code-based) scheduling methods have been proposed ([6], [7]). The basic idea of the currently proposed topology-transparent scheduling algorithms is for a node to transmit in a number of time slots in each frame. The time slots when node (i) transmits in a frame correspond to a unique code such that, for any given neighbor (k) of (i), node (i) has at least one transmission slot during which neither (k) nor any of (k)'s own neighbors are transmitting. Therefore, within any given time frame, any neighbor of (i) can receive at least one packet from (i) collision-free.

The limitations of the topology-transparent scheduling approaches described to date are that:

a) The sender is unable to know which neighbor(s) can correctly receive the packet it sends in a particular slot; therefore, these methods cannot be paired with RTS/CTS hand-shakes used to coordinate collision-free link activation between a particular sender and a particular receiver, or any process that requires the presence of only one active transmitter in a two-hop neighborhood, and

b) The number of time slots between 2 consecutive transmissions (of new packets) by the same node is proportional to $Dmax^2$; therefore, the efficiency of these methods drops quadratically as the density of the network increases.

c) These methods are not appropriate for networks that can exhibit significant variance in their density and/or size.

What is needed is a topology-transparent scheduling method that overcomes all of the above limitations.

II. STDMA OPERATION

STDMA is the generalization for mobile ad-hoc networks of the cellular TDMA with spatial re-use bandwidth allocation paradigm that is encountered in cellular TDMA networks.

In STDMA, space is divided into virtual geographic cells called space slots that are grouped into periodically repeating virtual frames (space frames) in order to facilitate spatial re-use, and time slots are assigned to space slots (fig 1). Each time slot is designed to accommodate the transmission of one fixed-size packet and a guard time, corresponding to the maximum differential propagation delay between pairs of nodes in the network.

STDMA is inherently topology-transparent, since time slot assignment depends on each node's instantaneous physical location, thus making it 'orthogonal' to connectivity changes. Therefore, STDMA is 'position-activated', as opposed to 'node-activated'. Every space slot is assigned its own time slot, and each node simply 'inherits' the time slot assigned to its current space slot. If K (K>1) nodes are co-located within the same space-slot, then they alternate transmitting during their assigned time slot on a round-robin basis (see fig 3); thus, each node transmits once (during its assigned time-slot) every K time frames.

In other words, STDMA is a 2-tier hierarchical TDMA protocol: in the first TDMA tier, time is 'looping' over space slots; in the second TDMA tier, time is 'looping' over the node IDs located within the same space slot.

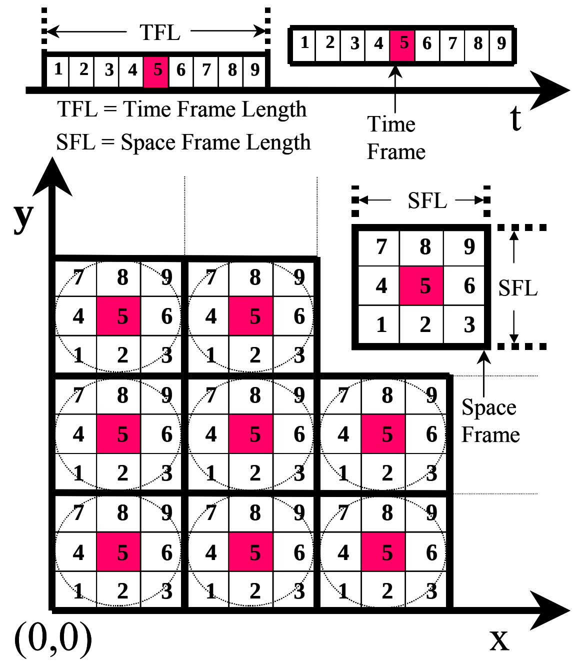

Fig 1: Graphical illustration of STDMA

The space frame is constructed such that SSD (see fig. 2), the distance between space slots that are assigned the same time slot ("simultaneous" space slots) is greater than 2 times the maximum transmission range; therefore, two simultaneous transmitters will never have any receivers in common. Thus, STDMA guarantees that there is only one active transmitter in a given 2-hop neighborhood, for any given time-slot, overcoming limitation (a). Therefore, STDMA can be readily paired with RTS/CTS handshaking mechanisms, in order to coordinate collision-free link activation of data time slots within a two-hop neighborhood. Also, as the upper bound analysis done in this paper shows, the maximum number of time slots between 2 consecutive transmissions by a node is linearly bounded by the maximum network degree (D_{max}), overcoming limitation (b). Finally, STDMA is inherently adaptable to variable network densities, and can support networks of unlimited size, overcoming limitation (c).

Let SFIL denote the Space Frame Integer Length (SFIL = 2, 3, ..). Then, the space slot length (SSL in fig. 2) is given by:

$$SSL = SSD / (SFIL - 1) \quad (1)$$

Thus, for SFIL equal to 3, and SSD equal to 2R, the resulting value of SSL is equal to the transmission range R, and the Time Frame Length (TFL = space frame area in slots) is equal to 9 (fig. 1).

Let Time Slot Sequence Number (TSSN = 0, 1, 2, …, ∞) denote a running time slot counter. Then, TSSN(t) can be written as:

$$TSSN(t) = t_F * TFL + t_S, \text{ where} \quad (2)$$
$$t_S = Mod[\ TSSN(t) / TFL\ ] + 1 \quad (3)$$
$$t_F = Floor[\ TSSN(t) / TFL\ ] \quad (4)$$

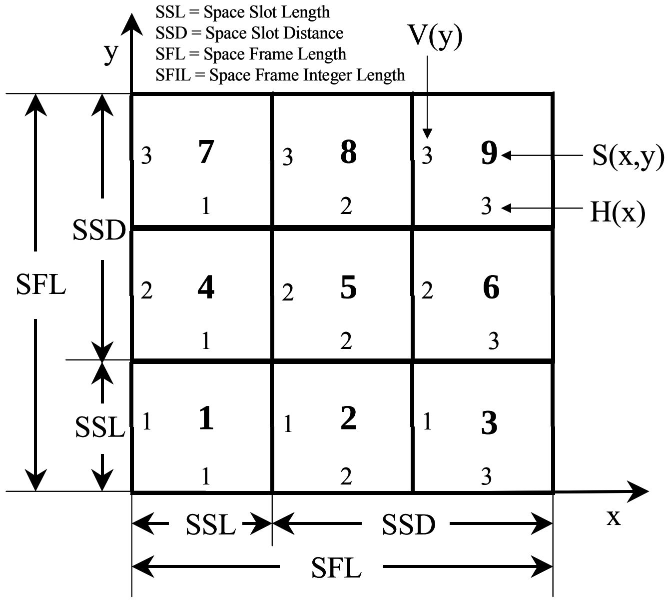

Fig. 2: Space Frame Construction/Timeslot Identification

Let (x, y) be the current position of a given node n, and define (see fig. 2):

$$H(x) = ceiling[mod(x / SFL) / SSL] \quad (5)$$
$$V(y) = ceiling[mod(y / SFL) / SSL] \quad (6)$$
$$S_n(x, y) = [V(y)–1] * (SFIL) + H(x) \quad (7)$$

Then, the set of time slots allocated to node n at time t have to satisfy:

$$t_S = S_n(x, y) \quad (8)$$

Let S(i, t) be the number of nodes that are co-located within space slot (i) at time t. Each node n continuously maintains a sorted ID list of all the nodes (including itself) co-located in space slot (i), and assigns itself a unique Conflict Resolution Index (CRI), where CRI ranges from 0 to S(i, t) – 1 (i.e., based on the relative numerical order of node n's ID within the sorted ID list) in order to facilitate collision-free time slot sharing amongst the nodes that are co-located within space slot (i). Then, the set of time slots allocated to node n has to also satisfy:

$$Mod[\ t_F / S(i, t)\ ] = CRI(n) \quad (9)$$

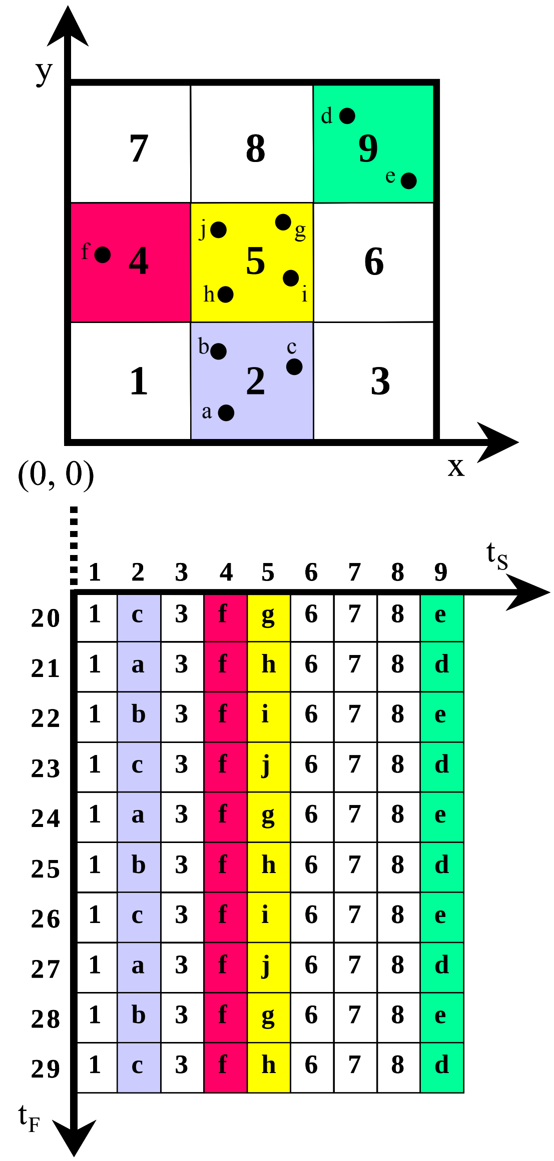

Fig. 3: Time slot sharing amongst co-located nodes

Fig 3 illustrates the sequence of transmissions for nodes that are co-located within the same space slot: nodes a, b, and c, located in space slot 2 [S(2, t) = 3], transmit once every 3 time frames; node f located in space slot 4 [S(4, t) = 1], transmits once every time frame since it's the only node located in its space slot; nodes g, h, i, and j, located in space slot 5 [S(5, t) = 4], transmit once every 4 time frames; nodes d and e, located in space slot 9 [S(9, t) = 2], transmit once every 2 time frames.

When a node (i) realizes that it is about to enter a new space slot, it broadcasts a Space Slot Update (SSU) packet containing a Time-To-Live (TTL) field, its current and future locations, the new and old space slot IDs, and a destination node ID located in the new space slot which has to respond with the sorted list of all nodes located in the new space slot.

The SSU packet is propagated TTL hops away from the source, allowing nodes in the old space slot to remove node (i) from their sorted node ID list, and nodes in the new space slot to insert node (i) in their sorted node ID list. The destination of the SSU packet responds by generating a Space Slot Update Response (SSUR) packet containing the sorted ID list of all nodes located in the new space slot that node (i) will enter. When the SSUR packet is received by node (i), node (i) has a complete sorted ID list of all nodes collocated in its new (future) space slot, and knows its CRI.

III. STDMA UPPER BOUND ANALYSIS

Let the random variable X(k, t) denote the number of time slots between successive transmissions by node k at time t, the random variable S(i, t) denote the number of nodes co-located in space slot (i) at time t, and L denote the total number of space slots in the network. Then, we have:

$$E_k(X, t)\ \frac{\text{slots}}{\text{node}} = \frac{\sum_{i=1}^{L} S(i,\ t)\ \text{nodes}\ * [S(i,\ t) * \text{TFL}]\ \frac{\text{slots}}{\text{node}}}{\text{N nodes}} \Rightarrow$$

$$E_k(X, t) = \frac{\text{TFL}}{\text{N}} * \sum_{i=1}^{L} S(i,\ t)^2\ \frac{\text{slots}}{\text{node}} \quad \text{where} \quad \sum_{i=1}^{L} S(i,\ t) = N$$

We observe that E[X] is minimized when TFL*$\Sigma[S^2]$ is minimized subject to ($\Sigma S = N$).

Next, we derive X_{max}, an upper bound on the number of time slots between successive transmissions by a given node.

$$X_{max} = \text{TFL} * S(i, t)_{max} = \text{SFIL}^2 * S(i, t)_{max}$$

Let D_{max} denote the maximum network degree.

Then, for SFIL ≥ 3 we have the following :

$$\text{SSL} = \frac{2R}{(\text{SFIL} - 1)} \leq R \Rightarrow \text{SSL}^2 \leq R^2 < \pi R^2 \Rightarrow$$

$$S(i, t)_{max} \leq D_{max} \Rightarrow X_{max} = \text{SFIL}^2 * D_{max}$$

For SFIL = 3 we then have :

$$X_{max} = 9D_{max}$$

The above upper bound is for the pathological case where Dmax nodes are all co-located within the same space slot of area R^2, and it is based on the simple inequality that the maximum number of nodes that can be co-located within a space slot [$S(i, t)_{max}$] of area R^2 cannot be greater than the maximum number of nodes (D_{max}) that can be located within the transmission range of a node (area = πR^2).

Thus, we have proved that by using Space-Time Division Multiple Access (STDMA), the number of time slots (X) between successive transmissions by a node is linearly bounded by the maximum network degree.

This is exponential improvement over the time frame lengths produced by currently proposed topology-transparent TDMA scheduling protocols ([6], [7]), which are proportional to the square of the maximum network degree.

IV. STDMA PERFORMANCE EVALUATION

In this section we present the STDMA performance evaluation results. The simulation parameters were as follows:

Network size = 500 nodes.

The network size was held constant for all scenarios.

Node transmission range = 5 km

Node Speed = 60 miles per hour

Node Direction: With 66% probability the node maintains the same direction, with 34% probability the node picks a new direction randomly between (0, 2π).

Position Update Interval = 10 seconds

If a node moves out of the network area [i.e., X(Y)(t) > MAX_x(y)], then X(Y)(t) = X(Y)(t) – MAX_x(y).

The average node degree took the following values: 4, 6, 8, 10, 12, 14, 16, 18, 20, 30, 40, and 50. Since the network size and transmission range were held constant in each run, the network area was varied in order to produce the different node densities.

SFIL took the following values: {2, 3, 4, 5, 6, 7}.

The measure of performance was the average number of time-slots (E(X)) elapsing between successive transmissions by a node.

Table 1 shows E(X) versus the average node degree (D_{avg}). The highlighted entries in the table indicate the SFIL values that produce the minimum value for E(X). As expected, the value of SFIL that minimizes E(X) increases with the average node degree. As can be seen, E(X) grows linearly with respect to the average node degree. We observe that the optimum E(X) ranges from $4D_{avg}$ (D_{avg} = 4) to about $2D_{avg}$ (D_{avg} = 50).

TABLE 1
AVERAGE NUMBER OF TIME SLOTS BETWEEN SUCCESSIVE TRANSMISSIONS BY A GIVEN NODE VS. AVERAGE NODE DEGREE

Average Node Degree	E(X) SFIL = 2	E(X) SFIL = 3	E(X) SFIL = 4	E(X) SFIL = 5	E(X) SFIL = 6	E(X) SFIL = 7
4	20	16	21	29	40	53
6	28	20	24	31	42	55
8	40	25	27	34	44	57
10	41	28	30	36	46	58
12	55	33	33	39	48	60
14	56	38	36	41	50	62
16	79	45	40	44	52	64
18	79	46	44	46	54	67
20	80	55	46	49	57	68
30	126	73	67	64	70	80
40	134	94	83	80	83	92
50	225	126	102	97	100	105

V. COORDINATED MACA

In this section, we apply STDMA as the multiple access scheme for the control channel (frame) of Coordinated MACA[8], a conflict-free reservation-TDMA link-activation protocol.

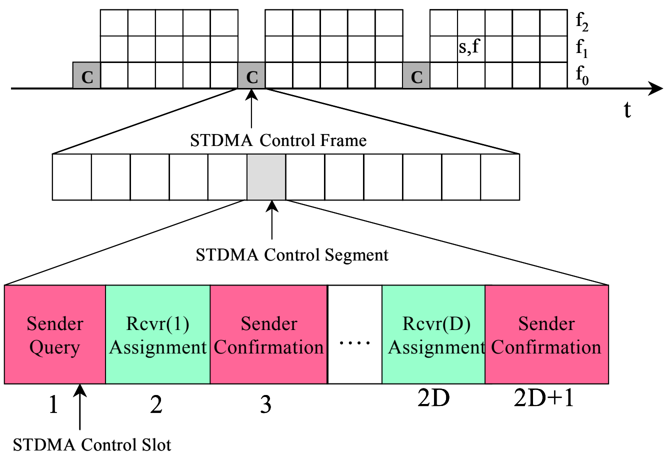

Fig. 4: Illustration of Coordinated MACA

Time is divided into time frames (fig. 4). Each time frame consists of a control frame (**C**) and a two-dimensional (slot - channel) data frame. The control frame is divided into control segments that are used to facilitate a link-activation negotiation between a sender, who sends assignment queries, and a set of intended receivers, who send assignment responses; thus, each control segment is further divided into a fixed number of control slots.

The first slot in each control segment is referred to as the query control slot. **The query control slots are accessed via STDMA**, according to the procedure outlined in the previous section.

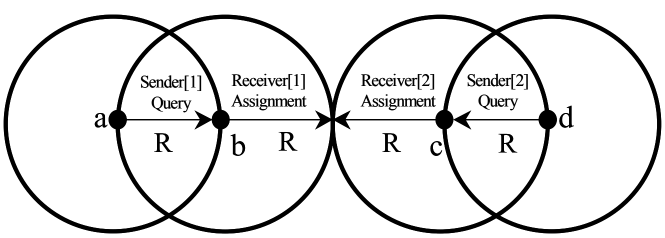

Fig. 5: Responding receivers (i.e., b and c assignment transmissions) have to be separated by 2R in order to prevent collisions at common neighbors

In order to guarantee that a slot assignment is conflict-free, knowledge of that assignment must be simultaneously received by:

a) The neighbors of the sender, so that they will not schedule 1) a receiving assignment, or 2) a transmission/reception to/from the sender during that slot, and
b) The neighbors of each receiver (rcvr), so that they will not schedule 1) a transmit assignment, or 2) a transmission/reception to/from the rcvr during that slot.

Thus, in order to achieve conflict-free slot assignments in a multi-hop packet radio network, it is required that a node initiating a reservation be unique within a 3-hop neighborhood, so that the responding receivers can be unique within their respective 2-hop neighborhoods.

STDMA, due to its innovative utilization of position information, can guarantee a unique transmitter within a 3-hop neighborhood with zero added complexity, or overhead: it is all done by simply setting SSD (see fig. 2) to 4R (instead of 2R, for the 2-hop unique transmitter case).

Therefore, in order to guarantee that the receiver (b, and c in fig. 5) assignment responses will be successfully received by every neighbor of each responding receiver, SSD (see fig. 2) is set to $4R_{max}$. This ensures that 'simultaneous' senders (a and d in fig. 5) are always separated by a distance greater than $4R_{max}$. Consequently, simultaneous responding receivers (b and c in fig. 5) are always separated by a distance greater than $2R_{max}$, ensuring that their assignment responses are received collision-free by each of their respective neighbors.

The space slot length (SSL) for the control channel space frame (see fig. 2) is given by:

$$SSL[\text{Control Channel}] = 4R / (SFIL - 1), \quad SFIL > 3$$

Using STDMA as the access scheme for the control frame, in combination with the sender-receiver handshake, ensures that knowledge of any slot assignments made is received successfully by:

a) Every neighbor of the sender, and
b) Every neighbor of each receiver.

Therefore, since each node in the network is aware, at all times, of all his neighbors' assignments (transmission and reception), no conflicting assignments can ever be made, resulting in maximal utilization of the data frame.

COORDINATED, POWER-AWARE LINK-ACTIVATION

We now show how Coordinated MACA can be used to coordinate the collision-free link activation of each node's links. We define the following variables:

(s, f) = (slot, channel). The channel (f) can be an FDMA channel or a CDMA channel.

X(s, f, i) = maximum power level that node (i) can use for transmitting on (s, f) without interfering with the reception assignments of any of its neighbors. When X(s, f, i) is equal to zero (s, f) is unavailable for future transmission assignments; this could happen if node (i) has already been assigned to transmit on (s, f), or a neighbor very close to node (i) has been assigned to receive on (s, f).

X(s, f, i) ranges from 0 to Maximum_Power_Level.

Initial Value [X(s, f, i)] = Maximum Power Level

X(s, f, i, j) = Node j's perception of X(s, f, i)

R(s, f, i) is a Boolean flag indicating the ability of node (i) to receive on (s, f). R(s, f, i) is set to 1 if node (i) is able to receive on (s, f), and set to 0 otherwise.

Initial Value [R(s, f, i)] = 1

P(i, j) = minimum power level at which i and j can successfully close the link between them. [P(i, j) = P(j, i)]

N(i, j) = minimum power level at which i and j can interfere with each other's receptions. [N(i, j) = N(j, i)]
In general, P(i, j) > N(i, j).

Transmission **A**ssignment **S**et (i) = TAS(i) =
{ [(s, f), X(s, f, i)] | X(s, f, i) > 0 for each (s, f) **}**
Set of [(s, f), Power] pairs that are advertised by node (i) as available for transmission assignments

Receive **A**ssignment **S**et (i) = RAS(i) =
{ (s, f) | R(s, f) > 0 for each (s, f) **}** = Set of (s, f) pairs that are available to node (i) for reception assignments

We now define the function UPDATE_STATE, which is the algorithmic response of a node triggered by the reception of a communication assignment event for (s, f). The function assumes that each node is equipped with a single half-duplex omni-directional transceiver. However, the function can be generalized for networks whose nodes are equipped with multiple transceivers, and/or directional antennas.
First, we define the following variables:
c = Current Node ID = Node ID of node processing the assignment event
a = Advertising Node ID = Node ID of node announcing the assignment event
x = Transmitter(s, f) = Node ID of node assigned to transmit on (s, f)
r = Receiver(s, f) = Node ID of node assigned to receive on (s, f)
p = Power(s, f) = Power level that will be used by the transmitter. This is assigned by the receiver, based on the perceived link quality between the sender and the receiver.

UPDATE_STATE (s, f, c, a, x, r, p)

```
IF (a = = r)                          (Receiver Assignment)
    IF (c = = x) OR (c = = r)
        X(s, f, c) := 0,  for all f;
        R(s, f, c) := 0,  for all f;
    ELSE                              (Receiver Neighbor)
        X(s, f, c) := N(c, r) – 1
ELSE
IF (a = = x)                          (Xmitter Confirmation)
    IF NOT[(c = = x) OR (c = = r)]    (Xmitter Neighbor)
        X(s, f, x, c) := 0
        IF p >= N(x, c)
            R(s, f, c) := 0;
```

We now describe the sender-receiver slot assignment negotiation that takes place during a particular control segment.

EVENT SEQUENCE (see fig. 4)

STEP[1]: SENDER = x
Sends a *query packet* advertising TAS[sender] to its intended receivers.
For i := 1 TO D (D = Number of intended receivers)
STEP[2i]: RCVR(i) = r(i)
a) Finds an (s, f) pair such that:
(R(s, f, r(i)) = 1) AND (X(s, f, x, r(i)) ≥ P(x, r(i)))
b) UPDATE_STATE[s, f, r(i), r(i), x, r(i), P(x, r(i))]
c) Sends an *assignment packet* containing [(s, f), P(x, r(i))]
d) For j:=1 to K (K = Number of Rcvr(i)'s neighbors)
UPDATE_STATE[s, f, n(j), r(i), x, r(i), P(x, r(i))]
STEP[2i+1]: SENDER = x
a) Sends a *confirmation packet* containing [(s, f), P(x, r(i))]
b) For k:=1 to L (L = Number of Sender's neighbors)
UPDATE_STATE[s, f, n(k), x, x, r(i), P(x, r(i))]

VI. Conclusion And Further Research

We presented Space-Time Division Multiple Access (STDMA), the first position-based TDMA scheduling algorithm for mobile, multi-hop ad-hoc networks.
To the author's knowledge, STDMA is the only topology-transparent TDMA scheduling algorithm that a) guarantees a unique transmitter within a 2-hop (or 3-hop) neighborhood, and b) produces time frame lengths that are linear with respect to the maximum network degree, therefore exponentially outperforming currently proposed topology-transparent scheduling algorithms which produce time frame lengths that are quadratic with respect to the maximum network degree.
We then applied STDMA as the access scheme for the control frame of coordinated-MACA, a reservation-based, conflict-free, power-aware link-activation protocol.
We are currently investigating the adaptation of STDMA and Coordinated-MACA for networks whose nodes are equipped with directional antennas.

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