Self-stabilizing TDMA Algorithms for Dynamic Wireless Ad-Hoc Networks*

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We consider *Medium Access Control* (MAC) protocols for Dynamic wireless ad-hoc networks (DynWANs) that need to be autonomous, robust, and have high bandwidth utilization, a high predictability degree of bandwidth allocation, and low communication delay in the presence of frequent changes to the network topology. We propose an algorithmic design for self-stabilizing MAC protocols with a provable short convergence period, and by that, it can facilitate the satisfaction of severe timing requirements and possesses a greater predictability degree, while maintaining low communication delays and high throughput. We show that the algorithm facilitates the satisfaction of severe timing requirements for DynWANs. We consider transient faults and topological changes to the communication network, and demonstrate self-stabilization.

Algorithm Description. The MAC algorithm in Fig. 1 assigns timeslots to nodes after the convergence period. The system consists of a set, P, of N anonymous communicating entities, which we call *nodes*. Denote every node $p_i \in P$ with a unique index, i. We assume that the MAC protocol is invoked periodically by synchronized *common pulse* that aligns the starting time of the TDMA frame [1]. The term *(broadcasting) timeslot* refers to the period between two consecutive common pulses. In our pseudo-code, we use the event timeslot (t) that is triggered by the common pulse. Nodes raise the event carrier_sense() when they detect that the received energy levels have reached a threshold in which the radio unit is expected to succeed in carrier sense locking. We assume that timeslots allow the transmission of DATA packets using the transmit() and receive() primitives. Moreover, we consider *signaling (beacons)* as short packets that include no data load, rather their carrier sense delivers important information. Before the transmission of the DATA packet in timeslot t, the scheme uses beacons for singling the node intention to transmit the packet within t. During the convergence period several nodes can be assigned to the same timeslot. The algorithm solves such timeslot allocation conflicts by letting node p_i to go through a (listening/signaling) competition with and node p_j before transmitting in its broadcasting timeslot. The competition rules require each node to choose one out of n listening/signaling period for its broadcasting timeslot. This

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Constants, variables, macros and external functions
  MaxRnd (n in the proofs) : integer = bound on round number
  s : [0, T-1] ∪ {⊥} = next timeslot to broadcast or null, ⊥
  signal : boolean = trying to acquiring the channel
  unused[0, T-1] : boolean = marking unused timeslots
  unused_set = { k : unused[k] = true } : unused timeslot set (macro)
  MAC_fetch()/MAC_deliver() : MAC layer interface
  transmit/receive/carrier_sense : communication primitives

Upon timeslot(t)
  if t = 0 ∧ s = ⊥ then s := select_unused(unused_set)
  (unused[t], signal) := (true, false) (∗ remove stale info. ∗)
  if s ≠ ⊥ ∧ t = s then send(MAC_fetch())

Upon receive(< DATA, m> ) do MAC_deliver(< m> )

Function send(m)   (∗ send message m to p'_i s neighbors ∗)
  for ((signal, k) := (true, 0); k := k + 1; k ≤ MaxRnd) do
    if signal then with probability ρ(k) = 1/(MaxRnd − k) do
      signal := false (∗ quit the competition ∗)
      transmit(< BEACON> ) (∗ try acquiring the channel ∗)
    wait until the end of competition round (∗ exposure period alignment ∗)
  if s ≠ ⊥ then transmit(< DATA, m> ) (∗ send the data packet ∗)

Upon carrier_sense(t) (∗ defer transmission during t ∗)
  if s = t ∧ signal then s := ⊥ (∗ mark that the timeslot is not unique ∗)
  (signal, unused[t]) := (false, false) (∗ quit the competition ∗)

Function select_unused(set) (∗ select an empty timeslot ∗)
  if set = ∅ then return ⊥ else return uniform_select(set)
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Fig. 1. Self-stabilizing TDMA-based MAC algorithm, code of node p_i.

implies that among all the nodes that attempt to broadcast in the same timeslot, the ones that select the earliest listening/signaling period win this broadcasting timeslot and access the communication media. Before the winners access their timeslots, they signal to their neighbors that they won by sending beacons during their chosen signaling periods. When a node receives a beacon, it does not transmit during that timeslot, because it lost this competition. Instead, it randomly selects another broadcasting timeslot and competes for it on the next broadcasting round.

Discussion. Thus far, MAC algorithms could not consider timing requirements within a provably short recovery period that follows (arbitrary) transient faults and network topology changes. This work proposes the first self-stabilizing TDMA algorithm for DynWANs that has a provably short convergence period. Thus, the proposed algorithm possesses a greater degree of predictability, while maintaining low communication delays and high throughput.

The analysis shows that when there are N nodes in the network and $\alpha \in (0,1)$, the network convergence time is bounded by equation (1) with probability $1-\alpha$, where n is the number of listening/signaling periods, d is the maximal node degree in the interference graph and T is the size of the TDMA frame. This means that with probability α all nodes are allocated with timeslots in maximum $k(n, N)$ broadcasting rounds, see Fig. 2.

$$\text{Convergence time:} \quad k(n,N) = 1 + \frac{log\left(1 - \sqrt[N]{1-\alpha}\right)}{log\left(1 - \left(\frac{n-1}{2n}\right)^{\frac{d}{T}}\right)} \tag{1}$$

Fig. 2 shows that the proposed algorithm demonstrates a low dependency degree on the number of nodes in the network even when considering $10,000$ nodes. We note that it uses merely a small fraction of the bandwidth that is spent on frame control information (say 3 listening/signaling periods) and when considering 99% probability to convergence within 30 to 35 TDMA frames.

The costs associated with predictable communications, say, using base-stations, motivate the adoption of new networking technologies, such as MANETs and VANETs. In the context of these technologies, we expect that our proposal would contribute to the development of MAC protocols that can be used by applications that need guarantees for severe timing requirements.

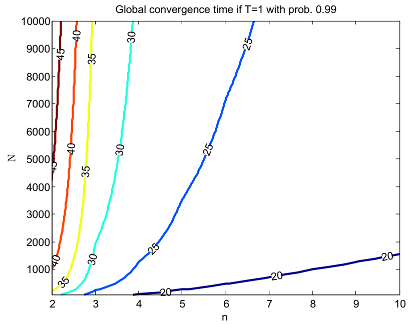

Fig. 2. Contour plot of equation (1) for $s = d/T = 1$. The contour lines connect values of $k(n, N)$ that are the same (see the text tags along the Contour lines). When N nodes attempt to access the medium, the conversance time is stable in the presence of a growing number, n, of listening/signaling periods.

References

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2. Leone, P., Schiller, E.M.: Self-stabilizing TDMA algorithms for dynamic wireless ad-hoc networks. arXiv 1210.3061, October 12 (2012), `http://arxiv.org/abs/1210.3061`