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

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Abstract: In dynamic wireless ad-hoc networks (DynWANs), autonomous computing devices set up a network for the communication needs of the moment. These networks require the implementation of a medium access control (MAC) layer. We consider MAC protocols for DynWANs that need to be autonomous and robust as well as have high bandwidth utilization, high predictability degree of bandwidth allocation, and low communication delay in the presence of frequent topological changes to the communication network. Recent studies have shown that existing implementations cannot guarantee the necessary satisfaction of these timing requirements. We propose a self-stabilizing MAC algorithm for DynWANs that guarantees a short convergence period, and by that, it can facilitate the satisfaction of severe timing requirements, such as the above. Besides the contribution in the algorithmic front of research, we expect that our proposal can enable quicker adoption by practitioners and faster deployment of DynWANs, such as the `IEEE 802.11p` for mobile ad hoc networks (MANETs) and vehicular ad-hoc networks (VANETs).

1 INTRODUCTION

Dynamic wireless ad-hoc networks (DynWANs) are autonomous and self-organizing systems where computing devices require networking applications when a fixed network infrastructure is not available or not preferred to be used. In these cases, computing devices may set up a short-lived network for the communication needs of the moment, also known as, an ad-hoc network. Ad-hoc networks are based on wireless communications that require implementation of a *Medium Access Control* (MAC) layer. We consider MAC protocols for 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 communication network topology. Existing implementations cannot guarantee the necessary satisfaction of timing requirements (Bilstrup et al., 2008; Bilstrup et al., 2009). This work proposes an algorithmic design for self-stabilizing MAC protocols that guarantees a short convergence period, and by that, can facilitate the satisfaction of severe timing requirements. The proposed algorithm possesses a greater degree of predictability, while maintaining low communication delays and high throughput.

The dynamic and difficult-to-predict nature of wireless ad-hoc networks gives rise to many fault-tolerance issues and requires efficient solutions. DynWANs, for example, are subject to transient faults due to hardware/software temporal malfunctions or short-lived violations of the assumed settings for modeling the location of the mobile nodes. Fault tolerant systems that are *self-stabilizing* (Dolev, 2000) can recover after the occurrence of transient faults, which can cause an arbitrary corruption of the system state (so long as the program's code is still intact), or the model of dynamic networks in which communication links and nodes may fail and recover during normal operation (Dolev and Herman, 1997). The proof of self-stabilization requires convergence from an arbitrary starting system state. Moreover, once the system has converged and followed its specifications, it is required to do so forever. The self-stabilization design criteria liberate the application designer from dealing

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with low-level complications, such as bandwidth allocation in the presence of topology changes, and provide an important level of abstraction. Consequently, the application design can easily focus on its task – and knowledge-driven aspects.

MAC **algorithms.** ALOHAnet and its synchronized version Slotted ALOHA (Abramson, 1985) are pioneering wireless systems that employ a strategy of "random access". Time division multiple access (TDMA) (Schmidt, 1974) is another early approach, where nodes transmit one after the other, each using its own timeslot, say, according to a defined schedule. The scheduled approach offers greater predictability of bandwidth allocation and communication delay, which can facilitate fairness (Herman and Tixeuil, 2004) and energy conservation (Ye et al., 2002).

There are two well-known approaches for dealing with contention (timeslot exhaustion): (1) employing policies for administering message priority, or (2) adjusting the nodes' individual transmission signal strength or carrier sense threshold (Yu and Biswas, 2007; Scopigno and Cozzetti, 2009). The former approach is widely accepted and adopted by the IEEE `802.11p` standard (see Section 4), whereas the latter has only been evaluated via computer simulations (Scopigno and Cozzetti, 2009).

STDMA (Yu and Biswas, 2007) and Viqar and Welch (Viqar and Welch, 2009) consider scheduling that is based on Global Navigation Satellite System (GNSS).

Related Work. We propose a self-stabilizing TDMA algorithm that does not require GNSS accessibility or knowledge about the node trajectories. Rather it considers an underlying self-stabilizing local pulse synchronization, such as (Mustafa et al., 2012).

When using collision-detection at the receiving-side (Scopigno and Cozzetti, 2009; Cozzetti and Scopigno, 2009; Yu and Biswas, 2007; Tadokoro et al., 2008; Lenoble et al., 2009), it is up to the receiving-side to notify the sender about collisions via another round of collision-prone transmissions, and by using FI (frame information) payload fields that includes T entries, where T is the TDMA frame size. Thus far, FI-based protocols study the stochastic resolution of message collision via computer network simulations (Yu and Biswas, 2007; Abrate et al., 2011; Scopigno and Cozzetti, 2010; Cozzetti et al., 2009; Tadokoro et al., 2008; Lenoble et al., 2009).

Simulations are also used for evaluating the heuristics of MS-ALOHA (Scopigno and Cozzetti, 2009) for dealing with contention (timeslot exhaustion) by adjusting the nodes' individual transmission signal strength and / or carrier sense threshold.

We do not consider lengthy frame information (FI) fields, which significantly increase the control information overhead, and yet we provide provable guarantee regarding the convergence time. Further analysis validation of the proposed algorithm via simulations and test bed implementation can be found in Section 5, and respectively, in (Mustafa et al., 2012).

The proposed algorithm does *not* consider collision-detection mechanisms that are based on signal processing or hardware support, as in (Demirbas and Hussain, 2006). Rather, it employs a variation on a well-known strategy for eventually avoiding concurrent transmissions among neighbors. This strategy allows the sending-side to eventually observe the existence of interfering transmissions. Before sending, the sender waits for a random duration while performing a clear channel assessment. A channel is considered to be used once the detected energy levels reach a threshold in which the radio unit is expected to succeed in carrier sense locking (details appear in Section 2 and (Leone and Schiller, 2012a)).

The proposed MAC algorithm can be entirely based on the carrier sensing of message transmission, as in (Cornejo and Kuhn, 2010), which focuses on fair bandwidth allocation, but does not consider dynamic networks or self-stabilization.

There are several proposals related to self-stabilizing MAC algorithms (Kulkarni and Arumugam, 2006; Arumugam and Kulkarni, 2005; Arumugam and Kulkarni, 2006; Lagemann et al., 2009; Herman and Tixeuil, 2004; Jhumka and Kulkarni, 2007); however, none of them consider dynamic networks and their frame control information is quite extensive. In (Leone et al., 2009a; Leone et al., 2010; Mustafa et al., 2012; Leone et al., 2009b), we consider a MAC algorithm that uses convergence from a random starting state (inspired by self-stabilization), were as here we consider self-stabilizing MAC algorithms. An extended survey of the related work appears in (Leone and Schiller, 2012a).

Our Contribution. This work proposes a self-stabilizing MAC algorithm that demonstrates rapid convergence without the extensive use of frame control information (Section 2). Our analysis shows that the algorithm facilitates the satisfaction of severe timing requirements for DynWANs (Section 3).

We start by considering transient faults and topological changes to the communication network, i.e., demonstrating self-stabilization. We then turn to focus on bounding the algorithm's convergence time after an arbitrary and unbounded finite sequence of transient faults and changes to the network topology. In particular, equation (2) shows that the expected local convergence time is brief, and equation (3) formulates the expected global convergence time. More-

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

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

Upon carrier_sense(t) (* defer transmission during t *)
 if $s = t \wedge signal$ then $s := \perp$ (* mark that the timeslot is not unique *)
 $(signal, unused[t]) :=$ (false, false) (* quit the competition *)

Function select_unused(set) (* select an empty timeslot *)
 if $set = \emptyset$ then return $\perp$ else return $uniform\_select(set)$

Upon timeslot(t)
 if $t = 0 \wedge s = \perp$ then $s :=$ select_unused($unused\_set$)
 $(unused[t], signal) :=$ (true, false) (* remove stale information *)
 if $s \neq \perp \wedge t = s$ then send(MAC_fetch())

Function send(m)   (* send message m to $p_i'$s neighbors *)
 for $((signal, k) := (\textbf{true}, 0); k := k + 1; k \leq MaxRnd)$ do
  if signal then with probability $\rho(k) = 1/(MaxRnd - k)$ do
   $signal :=$ false (* quit the competition *)
   transmit(< BEACON> ) (* try acquiring the channel *)
  wait until the end of competition round (* exposure period alignment *)
 if $s \neq \perp$ then transmit(< DATA, m> ) (* send the data packet *)
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Figure 1: Self-stabilizing TDMA-based MAC algorithm, code of node p_i.

over, for a given probability, the global convergence time is calculated in equation (4).

We protocol implementations that deal with situations in which there is a non-constant number of transmitting and neighboring terminals (Section 4).

Lastly (Section 5), we explain that when allowing a fraction of the bandwidth to be spent on frame control information and when considering any given probability to converge within a bounded time, the proposed algorithm demonstrates a low dependency degree on the number of nodes in the network.

Due to the space limit, the proofs appear in (Leone and Schiller, 2012a).

2 ALGORITHM DESCRIPTION

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.

TDMA protocols divide the radio time into frames, which are then divided in to T broadcasting timeslots, where T is an upper bound on the number of concurrently transmitting terminals in any given neighborhood. We call $\mathcal{N}_i$ the *(interference) neighborhood* of node $p_i \in P$ and $d_i = |\mathcal{N}_i|$ is named the (interference) degree of node p_i.

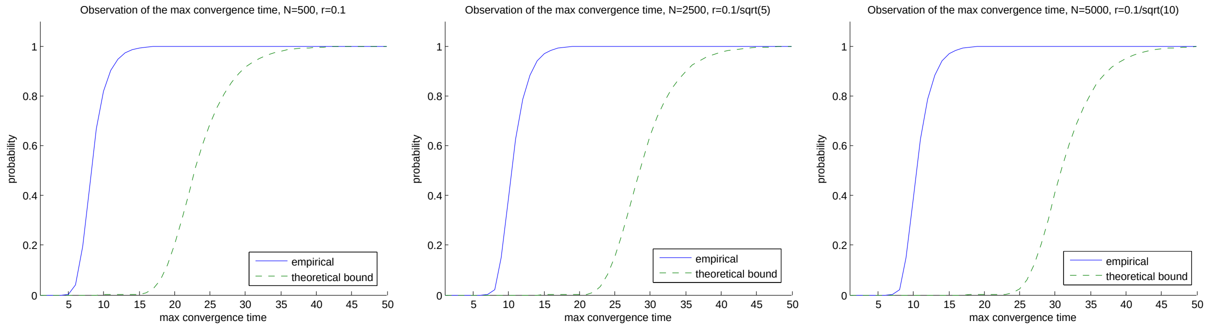
The MAC algorithm in Fig. 1 assigns timeslots to nodes after the convergence period. We assume that the MAC protocol is invoked periodically by synchronized *common pulse* that aligns the starting time of the TDMA frame (Mustafa et al., 2012). The term *(broadcasting) timeslot* refers to the period between 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 the node p_i and p_j to go through a (listening/signaling) competition before transmitting in its broadcasting timeslot. The competition rules require each node to choose one broadcasting timeslot out of n listening/signaling periods. This 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.

3 CORRECTNESS

The proof starts by considering no changes to the network topology and that the ratio between the node extended degree and the frame size is less than one, i.e., $\forall p_i \in P : 1 \lesssim T/d_i$ (see Section 4 for extensions). We continue by focusing on the converge period for a single neighborhood and the entire network. These convergence estimations facilitate the exploration of important properties for dealing with changes in the



(a)

(b)

(c)

Figure 2: Numerical validation of equation (3), which bounds the network-wise convergence time. We compare the bound, $P(t_{\max} < k) = (1-(1-q)^k)^N$, with the numerical results, which consider random geometric graphs in which the nodes are randomly placed on the unit square. The charts considers $N \in \{500, 2500, 5000\}$ nodes (from left to right). All experiments considered 2 listening/signaling periods, interference range of $0.1/\sqrt{(\frac{N}{500})}$, which result in an average extended degree of 15, $d_i/T = 1$ on average, and $q_i = 1/4$.

network topology. Due to the space limit, the proofs appear in (Leone and Schiller, 2012a).

The proof delineates the different states at which a node can be in relation to its neighbors, and groups these states into three categories of *relative states*: (1) Ready to be allocated, when the node state depicts correctly its neighbor states, (2) Obtaining a timeslot, when the node is competing for one, but there is no agreement with its neighbor states, and (3) Allocated to a timeslot, when the node is the only one to be allocated to a particular timeslot in its neighborhood.

The self-stabilization proof shows that, starting from an arbitrary starting configuration, each node eventually reaches the relative state Allocated. $OnlyOne_i(x)$ is the probability that a node enters the relative state Allocated from either Ready or Obtaining, where n is the number of listening/signaling periods, T the TDMA frame size, d_i is p_i's extended degree, and $\rho_k = 1/MaxRnd = 1/n$ is p_i's probability to select the k-th listening/signaling period for transmitting its beacon.

$$OnlyOne_i(x) \geq \sum_{k=1}^{n} \rho_k \left(1 - \sum_{\ell=1}^{k} \rho_k\right)^{\frac{d_i}{T}} \tag{1}$$

Neighborhood Convergence The expected time, $\mathcal{S}_i$, for node $p_i \in P$ to reach the relative state Allocated satisfies equation (2). Note that $\mathcal{S}_i \leq 4$ when the number of listening/signaling periods is $n \geq 2$. Namely, the proposed algorithm convergence with a neighborhood is brief.

$$\mathcal{S}_i \leq \min\{\left(\frac{2n}{n-1}\right)^{\frac{d_i}{T}}, \frac{\frac{d_i}{T}+1}{n}\left(\frac{n}{n-1}\right)^{\frac{d_i}{T}+1}\} \tag{2}$$

Network Convergence. The expected number of retransmissions is smaller than $\left(\frac{2n}{n-1}\right)^{d/T} - 1$, where $d = \max(\{d_i : p_i \in P\})$. Hence, we have that the expected number of broadcasting rounds, $\mathcal{S}$, that guarantee that all nodes reach the relative state Allocated satisfies equation (3).

$$\mathcal{S} \leq \left(\frac{2n}{n-1}\right)^{d/T} \tag{3}$$

Moreover, given that there are N nodes in the network and $\alpha \in (0,1)$, the network convergence time is bounded by equation (4) with probability $1-\alpha$.

$$k = 1 + \frac{log\left(1 - \sqrt[N]{1-\alpha}\right)}{log\left(1 - \left(\frac{n-1}{2n}\right)^{\frac{d}{T}}\right)} \tag{4}$$

This means that with probability α all nodes are allocated with timeslots in maximum k broadcasting rounds, see Fig. (3).

We numerically validate equations (3) and (4) in Fig. 2, and respectively, Fig. 3. Note that these experiments show that the average convergence time of the network is below the upper bound of equation (3).

4 IMPLEMENTATION

We mention mechanisms for dealing with timeslot exhaustion, see details in (Leone and Schiller, 2012a).

Peritonized Listening/Signaling Periods. One can consider listening period parameters, $[LSP_{start}, LSP_{end}]$, that refer to the first, and respectively, the last listening/signaling periods that a node can use when attempting to acquire a broadcasting timeslot. E.g., suppose that there are six listening/signaling periods, and that nodes with the highest priory may use the first three listening/signaling periods, $[0,2]$, and nodes with the lowest priority may use the last three, $[3,5]$. In the case of two neighbors with different listening period parameters, say $[0,2]$ and $[3,5]$, that attempt to acquire the same broadcasting timeslot, the highest priority node always attempts to broadcast before the lowest priority one.

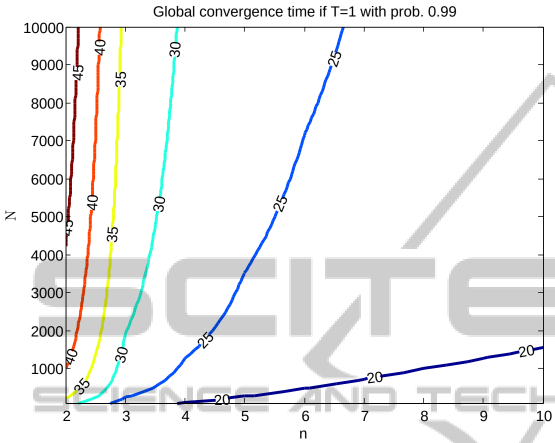


Figure 3: Contour plot of equation (4) for $s = d/T = 1$. The contour lines connect values of $k(n,N)$ that are the same (see the text tags along the Contour lines), where N is the number of nodes and n is the number of signaling periods.

TDMA-based Back-off. Let us consider two back-off parameters, CW_{start} and CW_{end}, that refer to the maximal and minimal values of the contention window. Before selecting an unused timeslot, the procedure counts a random number of unused ones. Fig. 4 presents an implementation of the select_unused() function that facilitates back-off strategies as an alternative to the code presented in Fig. 1.

The statically allocated variable *count* records the number of backoff steps that node p_i takes until it reaches the zero value. Whenever the function select_unused() is invoked with $count_i = 0$, node p_i assigns to $count_i$ a random integer from $[CW_{start}, CW_{end}]$. Whenever the value of $count_i$ is not greater than the number of unused timeslots, the returned timeslot is selected uniformly at random. Otherwise, a $\perp$-value is returned after deducting the number of unused timeslots during the previous broadcasting round.

5 DISCUSSION

Thus far, both schedule-based and non-schedule-based 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.

In this discussion, we would like to point out the algorithm's ability to facilitate the satisfaction of severe timing requirements for DynWANs by numerically validating equations (3) and (4). As a case study, we show that, for the considered settings of Fig. 2, the global convergence time is brief and definitive. Fig. 3 shows that the proposed algorithm demonstrates a low dependency degree on the number of nodes in the network even when considering 10,000 nodes by merely using small fraction of the bandwidth to be spent on frame control information (say 3 listening/signaling periods) and when considering 99% probability to convergence within 30 to 35 TDMA frames.

We have implemented the proposed algorithm, extensively validated our analysis via computer simulation, and tested it on a platform with more than two dozen nodes, see (Mustafa et al., 2012). These results indeed validate that the proposed algorithm can indeed facilitate the implementation of MAC protocols that guarantee satisfying these severe timing requirements, such as MANETs and VANETs.

```
Addtional constants and variables
  $CW_{start}$ and $CW_{end}$ : backoff parameters
  $count$ : statically allocated variable that counts the backoff steps

Function select_unused($set$)
  let $rtn\_val = \perp v$ // indicate busy channel (default return value)
  if $count \leq 0$ then $count \leftarrow uniform\_select([CW_{start}, CW_{end}])$
  $count \leftarrow count - |set|$
  if $count \leq 0$ then $(count, rtn\_val) \leftarrow (0, uniform\_select(set))$
  return $rtn\_val$
```

Figure 4: select_unused() with TDMA-based back-off

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