Analytical Study of Self Organizing TDMA for V2X Communications

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Abstract—**Self-Organizing TDMA (S-TDMA) is a channel access technique based on a time-slotted channel and distributed slot reservation procedure. It is considered as a valid alternative to the Dedicated Short Range Communication (DSRC) standard for safety-critical (V2X) communications, because of its stable deterministic access opportunity and delay under various channel loads. This paper provides an analytical model of S-TDMA to compute the Slot Occupation Distribution and Packet Level Incoordination in closed-form expression. By means of the proposed model, we then provide an asymptotic evaluation of the impact of various configuration parameters on the communication performance of S-TDMA.**

I. Introduction

Self-organizing Time Division Multiple Access (S-TDMA) has been recently proposed [1], and formally described by the ETSI [2], as an alternative channel access protocol for V2X communications. Compared to the current standard Dedicated Short Range Communication (DSRC), also called ITS-G5 in Europe, S-TDMA shows salient qualities for safety-critical vehicle-to-everything (V2X) communications, such as a stable deterministic channel access and predictable delay, under various loads of the shared vehicular channel. A deterministic channel access is notably critical to future Day Two V2X applications, such as Platooning or Cooperative Adaptive Cruise Control (C-ACC), both being under tight real-time constraints.

S-TDMA has been intensively simulated over the past few years in order to evaluate its convergence [3] and stability [4] to high channel load or to scenarios (propagation range and decoding capabilities) [5], [6]. To best of our knowledge, no comprehensive analytical model of S-TDMA exists. In [7], the authors mathematically derive the probability of slot collisions, but considering only a subset of the algorithm parameters. Compared to simulations, analytical models allow a larger flexibility in the evaluation space. Analytical evaluations also have the advantage of not being bound to specific scenarios, and as such, are critical to asymptotic performance evaluations.

In this paper we propose a detailed analytical model of S-TDMA, and provide an analysis of the Packet Level Incoordination (PLI) and the Slot Occupation Distribution (SOD) in closed-form expression. We also evaluate the impact of various parameters on the asymptotic performance of S-TDMA. As few abstractions as possible are made to remain close to the real protocol behavior, while achieving analytical tractability.

The rest of the paper is organized as follows: in section II related works are presented; in section III, S-TDMA is briefly described; in section IV the performance metrics are defined and the analytical model is described in detail. In section V PLI and SOD are illustrated for various protocol configurations; finally, section VI concludes the paper.

II. Related Work

Numerous research studies have recently focused on S-TDMA, an alternative channel access technique based on a time-slotted channel and distributed slot reservation procedure, already being exploited for position reporting in maritime [8] and airborne [9] environments. Due to its structured medium access mechanism, S-TDMA has shown many properties desirable for safety-critical communications.

In [10], Sjöberg et al. show that the synchronized nature of S-TDMA offers better performances than DSRC in terms of Packet Reception Probability, regardless of the presence of hidden terminals. In [4], the same authors also highlight the increased scalability of S-TDMA w.r.t DSRC, thanks to its virtual immunity against undesired packet collisions due to concurrent transmissions.

A further important property of S-TDMA is the deterministic channel access delay, whereas in DSRC such delay could grow unpredictably in highly loaded scenarios. In [3] Alonso and Mecklenbräuker study the stabilization time of S-TDMA, i.e. the time necessary for the protocol to reach a stable performance. DSRC achieves better stabilization time than S-TDMA in lightly loaded scenarios, but the stabilization time increases with growing channel loads, whereas S-TDMA continues to offer stable performances in high density networks.

On the other hand, Gaugel et al. [5] recently conducted an in-depth evaluation study of the structure of S-TDMA, showing that it offers better performance than CSMA-CA only in ideal scenarios, in which transmissions are not heavily affected by channel-induced errors. In [6], they further show that the superiority of one protocol over the other is dependent on the the considered scenarios.

A detailed analytical study of S-TDMA, which could help understanding how every aspect of the protocol theoretically affects its performances, is still missing in literature and is therefore the subject of this work.

III. Protocol Description

In this section, S-TDMA is briefly introduced. For a more detailed description, we invite the reader to refer to [5].

S-TDMA is a structured channel access mechanism, in which the time dimension of the channel is divided into fixed length slots, whose duration, for V2X applications, is suited to host one Cooperative Awareness Message (CAM) packet plus a necessary guard interval. Hence, the number N of available slots per second depends on the channel and packet characteristics: considering a 10 MHz wide Control Channel with 6 Mbps transfer rate, this translates to $N = 2016$ slots/s for 300 bytes CAMs and to $N = 859$ slots/s for 800 bytes CAMs ([2] - §5.2.3.1). Terminals are required to be synchronized at slot level, meaning that the starting and finishing instants of each slot must be aligned for all the users. Every user further organizes the time resources into a periodical structure of *frames* 1s long [2], each containing N consecutive slots. Frame alignment is not necessary, so users choose the starting slot for their frames randomly, at the moment they join the network.

The medium access policy is based on a slot reservation process: terminals autonomously reserve the slots they are going to use for their transmissions based on other users' geographical position and slots reservation information, which has to be included into every packet. This process is organized into 4 phases, which are sequentially performed when a new user enters the network: *initialization*, *network entry*, *first frame phase* and *continuous operations*.

In the *initialization* phase, a terminal listens to the channel for 1 frame and maps the state of all its N slots. The possible states that a slot can assume are:

- *free*, if the slot is not being reserved by any user;
- *externally allocated*, if the slot is allocated for transmission by another user;
- *internally allocated*, if the slot will be used by the current user.

The purpose of the *network entry* phase is for a terminal to advertise its presence to the network. To do so, a terminal transmits a one-time *network entry packet* in one of the first slots sensed free in the previous phase, randomly chosen according to a p-persistent mechanism.

Once the network is aware of the presence of the new terminal, it is time for it to allocate a sufficient number of transmission slots to satisfy its report rate of r packets per second. Denoting with $\sigma_0, \ldots, \sigma_{N-1}$ the slots within each frame as numbered by the current terminal, the *first frame phase* develops as follows:

1) a Nominal Increment (NI) is defined as NI $= \lfloor N/r \rfloor$, representing the ideal interval between two consecutive transmitted packets;
2) a Nominal Starting Slot (NSS) is randomly chosen among the free slots within the first NI ones;
3) further $r-1$ Nominal Slots (NS) are identified starting from the NSS, each spaced NI slots from the previous one. Denoting with ν the coordinate of the NSS, the coordinate of the i^{th} NS is $\sigma_{\nu+i\cdot NI}$;
4) around the NSS and the NSs, Selection Intervals (SI) are defined, each including the s·NI slot surrounding them. The cardinality of the SI is determined by its ratio s wrt the NI, with $0 < s \leq 1$. The SI of the i^{th} NS is:
$$SI_i = \left\{\sigma_j \mid \nu+i\cdot\mathrm{NI}-\left\lfloor\frac{N}{2r}s\right\rfloor\leq j\leq \nu+i\cdot\mathrm{NI}+\left\lfloor\frac{N}{2r}s\right\rfloor\right\} \quad (1)$$
where the NSS is the NS with index $i = 0$.
5) within the SI, a Candidate Set (CS) of slots is compiled according to the following rules:
   - free slots are automatically included in the CS;
   - the minimum size for the CS is w_{CSmin}. If less than w_{CSmin} free slots are available in the SI, a suitable number of externally allocated ones must be included in the CS. Those are selected starting from the ones allocated by the users more distant from the current transmitter;
   - the designated slot for the transmission, called Nominal Transmission Slot (NTS), is randomly chosen from the ones in the CS with uniform probability, regardless of its state.

   In case the NTS is an externally allocated slot, the current terminal will not be able to reuse slots allocated by that same user in the current frame. For this reason, in [8] §3.1.6 the states *available* and *unavailable* for externally allocated slots are defined.

Fig. 1 schematically represent the first frame phase.

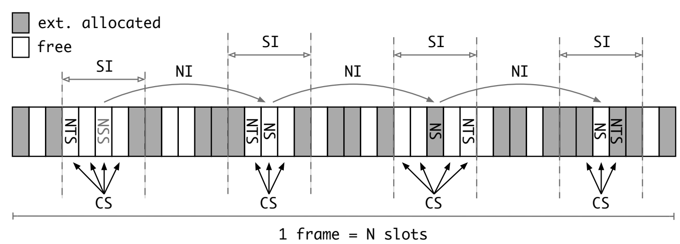

Fig. 1. Slot reservation process: *first frame phase*, $w_{CSmin} = 3$. In the SI on the right, two ext. allocated slots had to be included in the CS and a slot reuse is produced (NTS is an externally allocated slot).

Terminals attach to every NTS a *timeout counter*, whose initial value is randomly chosen between t_{min} and t_{max}, which is decremented by one unit every frame. When the timeout expires, a new NTS must be reserved, following the same aforementioned rules. This re-reservation mechanism aims at reducing the effect of systematic collisions between terminals due to overlapping reservation patterns. The information about the timeout counter, along with the coordinate of the following allocated slot must be included in each transmitted packet.

In the *continuous operation* phase, users continue to re-reserve slots for transmission applying the mechanism described in the first frame phase.

IV. Model Description

The purpose of this work is to compute the asymptotic Slot Occupation Distribution of S-TDMA as defined in [6], i.e the probability distribution for one slot to be reused by i users. The Packet Level Incoordination [5], i.e. the probability for a transmitting user to have one reserved slot being reused by other terminals, can then be derived directly from the SOD.

In order to achieve analytical tractability, we must make the following abstractions:

- as we focus on evaluating the steady state behavior of the reservation process, we assume a network of users already aware of each other's presence. Hence, only the *continuous operations* phase is modeled;
- the CS is compiled without knowing the reservation pattern of concurrent users: instead, slots are added based on their probability of being sensed free;
- when necessary, the externally allocated slot to include in the CS will be chosen randomly, instead of based on the relative distance between the contending terminals;
- being our focus on MAC layer performance, we assume a perfect PHY layer. Fading would indeed impair the probability of reception, but also reduce the number of terminals competing for the same channel resources;
- terminals are either static or in homogeneous mobility.

To describe the behavior of S-TDMA we need to model two processes:

A) the *timeout mechanism* terminals associate to each NTS;
B) the *slot re-reservation* mechanism.

Despite the protocol being structured deterministically, aspects such as the distribution of the allocated slots and the choice of the NTSs are inherently random, making the state of the system at any point in time and space a random process. Both A) and B) will thus be described with stochastic models.

A. Timeout process (π_t)

The timeout mechanism determines for how many consecutive frames one user reserves each of its NTSs. When the counter reaches its minimum value, a re-reservation event is triggered and a new timeout is chosen. Assuming that users always have r packets per frame to transmit and 1 being the minimum value of the counter, we can model the timeout process as a discrete-time Markov Chain, whose state diagram is represented in Fig. 2. The time unit is 1 frame, since this is the counter update interval. Denoting with $\pi_{t,i}$ the steady state

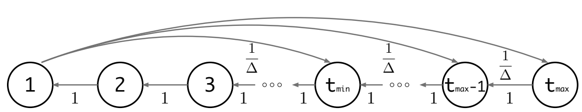

Fig. 2. Markov Chain associated to the timeout mechanism

probability for the counter to be in state i, we can compute the stationary distribution as follows:

$$
\begin{aligned}
&\pi_{t,t_{max}} = \pi_{t,1}/\Delta && \\
&\pi_{t,i} = \pi_{t,1}/\Delta + \pi_{t,i+1} && t_{min} \leq i < t_{max} \\
&\pi_{t,i} = \pi_{t,t_{min}} && 1 < i < t_{min}
\end{aligned}
$$

with $\Delta = t_{max} - t_{min} + 1$. Imposing the normalization condition:

$$\sum_{i=1}^{t_{max}} \pi_{t,i} = 1$$

we can obtain $\pi_{t,1}$, the probability for a slot re-reservation event to take place.

B. Slot re-reservation process

Let us consider an isolated network of N_t terminals (users) within each other's transmission range. Let us then consider a chunk χ of NI consecutive time slots: on average, we can assume that all of the N_t users will need to transmit in exactly one of these NI slots. Among these NI, we identify one generic slot σ_t, we will refer to as the *tagged slot*. The re-reservation process, from the perspective of the tagged slot, can be modeled with the discrete-time Markov chain depicted in Fig. 3. Again, the time unit is 1 frame, being 1 frame the time interval between timeout counter value updates. The

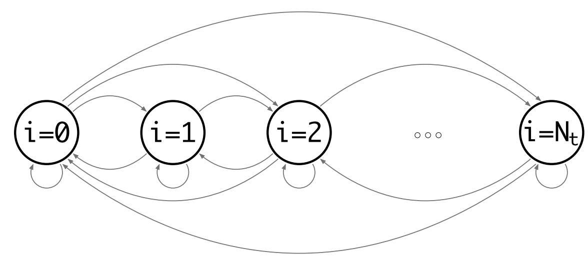

Fig. 3. Markov Chain of the reservation process as seen by the tagged slot. The state variable i is the number of terminals reusing the tagged slot.

state variable i represents the number of terminals currently reusing the tagged slot. The tagged slot will thus be free for $i = 0$, allocated by a single user for $i = 1$ and reused by multiple users when $i > 1$. The extreme theoretical case is represented by the tagged slot being contemporarily allocated by all of the N_t users, while all of the other NI -1 slots in χ are free. Denoting with π_i the steady state probability for the tagged slot to be in state i, the stationary distribution $\boldsymbol{\pi} = \{\pi_0, \ldots, \pi_{N_t}\}$ represents the SOD we are interested in.

Denoting with $p_{i,i+j}$ the probability for the process to transition from state i to state $i+j$, the SOD can be computed solving the following equation:

$$\boldsymbol{\pi} = \boldsymbol{\pi}\mathbf{P} \tag{2}$$

where $\mathbf{P}$ is the transition probability matrix:

$$\mathbf{P} = \begin{pmatrix} p_{0,0} & p_{0,1} & \cdots & p_{0,N_t} \\ p_{1,0} & p_{1,1} & \cdots & p_{1,N_t} \\ \vdots & \vdots & \ddots & \vdots \\ p_{N_t,0} & p_{N_t,1} & \cdots & p_{N_t,N_t} \end{pmatrix}.$$

In order to compute a general expression for $p_{i,i+j}$ with $0 \leq i \leq N_t$, $0 \leq i+j \leq N_t$, we define the following events:

- an *arrival* in the tagged slot happens when a user in the process of re-reserving its transmission slot within χ choses the tagged slot as its NTS;
- a *departure* from a generic slot in χ happens when the timeout of one of the users that were previously allocating it expires, thus forcing that user to reserve a new NTS.

$$p_i\{\overline{d}, a \mid d\} = p_i\{\overline{D} = \overline{d} \mid D = d\} \cdot p\{A = a \mid D = d\} =$$
$$\binom{i}{\overline{d}}\binom{N_t - i}{d - \overline{d}}{\pi_{t,1}}^d(1-\pi_{t,1})^{N_t - d} \cdot \sum_{k=a}^{d}\binom{d}{k}{p_{SI}}^k(1-p_{SI})^{d-k} \cdot \binom{k}{a}p^a(1-p)^{k-a} \tag{6}$$

Since the timeout processes of the N_t users are independent from each other, so are the departure events that involve them. Denoting with D the number of departures that occur in χ and with $\overline{D}$ the number of departures that occur in the tagged slot, we have that the probability of having a total of d departures in χ of which $\overline{d}$ are from the tagged slot while it is in state i can be computed as:

$$p_i\{\overline{D} = \overline{d} | D = d\} = \binom{i}{\overline{d}}\binom{N_t - i}{d - \overline{d}}{\pi_{t,1}}^d(1-\pi_{t,1})^{N_t - d} \tag{3}$$

with $0 \leq \overline{d} \leq i$, as the number of departures from the tagged slot cannot exceed the number of users currently reserving it.

Let us now consider the arrival events in the tagged slot. For an arrival to occur, the following conditions must verify:

1) somewhere in χ one or more departures must occur;
2) one of the departing users' SI includes the tagged slot;
3) the tagged slot is included into the CS;
4) the tagged slot is chosen as the NTS.

The probability of having $A = a$ arrivals in the tagged slot must then be conditioned on having $d \geq a$ departures in χ. The probability for the tagged user to belong to the SI of one generic re-reserving user is given by[1]:

$$p_{SI} = p\{\sigma_t \in SI\} = \min\left\{\frac{|SI|}{NI}, 1\right\} \tag{4}$$

where $|SI|$ represents the cardinality of SI, i.e. the number of slots in SI. The probability to have $A = a$ arrivals in the tagged slot given that d departures occur in χ can then be expressed as:

$$p\{A = a \mid D = d\} =$$
$$\sum_{k=a}^{d}\binom{d}{k}{p_{SI}}^j(1-p_{SI})^{d-k}\binom{k}{a}p^a(1-p)^{k-a} \tag{5}$$

where p represents the probability for the tagged slot to be chosen by a re-reserving user as its next NTS, given that σ_t belongs to that user's SI.

By combining (3) and (5) we can finally obtain the probability $p_i\{\overline{d}, a \mid d\}$ of having a arrivals in the tagged slot and $\overline{d}$ departures from it, given that d total departures happen in χ and σ_t is in state i as in equation (6).

Finally, the probability $p_{i,i+j}$ can be obtained as the sum of all the probabilities of the combinations of events such that the balance between the arrivals in the tagged slot and the departures from it is equal to j. Mathematically, this translates to:

$$p_{i,i+j} = \sum_{C_{i,i+j}} p_i\{\overline{d}, a | d\} \tag{7}$$

[1] *min* operation is necessary as it can be $|SI| > NI$ when $s = 1$ in (1).

where the set of conditions $C_{i,i+j}$ is defined as follows:

$$\begin{aligned}
&C_{i,i+j}:\\
&0 \leq d \leq N_t\\
&0 \leq \overline{d} \leq min\{i, d\}\\
&0 \leq a \leq d\\
&j = a - \overline{d}
\end{aligned}$$

To be able to compute (7) we still need to determine p, that appears in (5) and (6). According to the S-TDMA protocol, the probability for a slot to be chosen as NTS by one re-reserving user (given that it belongs to its SI) depends on the state the tagged slot is sensed to be in.

a) The tagged slot is sensed free: If the tagged slot is sensed free, it is automatically included into the candidate set of the re-reserving user, from which the NTS is chosen with uniform probability. We then have that the probability for the tagged slot to be chosen while sensed free p_f is:

$$p_f = \frac{1}{\max\{\mathbb{E}[n_f], w_{CSmin}\}} \tag{8}$$

where $\mathbb{E}[n_f]$ is the expected number of free slots within the SI and can be computed as:

$$\mathbb{E}[n_f] = \sum_{k=1}^{|SI|} k \cdot \binom{|SI|}{k}\hat{p}^k(1-\hat{p})^{|SI|-k}$$

with $\hat{p}$ being the probability for one slot to be sensed free.

b) The tagged slot is sensed allocated: If the tagged slot is sensed allocated, it only has a chance to be part of the candidate set of a re-reserving user if there are less than w_{CSmin} free slots within its SI. Specifically, if $\overline{n_f}$ slots are free within the SI, with $\overline{n_f} < w_{CSmin}$, we have that:

$$p\{\sigma_t \in SI \mid \text{allocated} \wedge \overline{n_f}\} = \frac{w_{CSmin} - \overline{n_f}}{|SI| - \overline{n_f}}.$$

The probability for the tagged slot to be part of the CS while allocated is then:

$$p\{\sigma_t \in SI \mid \text{allocated}\} =$$
$$= \sum_{k=0}^{w_{CSmin}-1} \frac{w_{CSmin} - k}{|SI| - k} \cdot \binom{|SI|}{k}\hat{p}^k(1-\hat{p})^{|SI|-k}$$

Since the NTS is again chosen with uniform probability from the CS, the resulting probability p_a for the tagged slot to be chosen while allocated is:

$$p_a = \frac{1}{w_{CSmin}} \cdot \sum_{k=0}^{w_{CSmin}-1} \frac{w_{CSmin} - k}{|SI| - k} \cdot \binom{|SI|}{k}\hat{p}^k(1-\hat{p})^{|SI|-k} \tag{9}$$

The probability p in equations (5) and (6) must then be chosen between p_f and p_a according to the state the tagged slot is sensed being in. Since a slot is sensed free when, during the previous frame:

- it was free and no other user reserved it;
- it was allocated by i users and all of them have to perform a re-reservation in the current frame;

in (5) and (6) we must set:

$$\begin{cases} p = p_f & \text{if } i = 0 \vee \overline{d} = i; \\ p = p_a & \text{otherwise.} \end{cases}$$

Following the same principle we can finally determine $\hat{p}$, the probability for a slot to be sensed free, as follows:

$$\hat{p} = \sum_{k=0}^{N_t} \pi_k^{(ff)} \cdot \pi_{t,1}{}^k \tag{10}$$

where $\pi_k^{(ff)}, 0 \leq k \leq N_t$ is the resulting SOD after that all the N_t users have finished their first frame phase, entering the network. By computing (2), we can evaluate the asymptotic performance of the S-TDMA protocol configuration evolving from an initial state distribution $\boldsymbol{\pi}^{(ff)} = \{\pi_0^{(ff)}, \ldots, \pi_{N_t}^{(ff)}\}$.

Finally, we can compute the Packet Level Incoordination experienced by a user allocating the tagged slot as the probability for the tagged slot to be reused by more than 1 terminal:

$$PLI = \sum_{k=2}^{N_t} \pi_k. \tag{11}$$

V. RESULTS

In this section the SOD and PLI for S-TDMA are evaluated by computing the proposed algorithm in MATLAB for different parameters configurations. These metrics are specific to S-TDMA and well describe the behavior of the slot reservation process. Packet delivery ratio can be computed starting from them, once further hypotheses on transmission range and terminals disposition (out of the scope of this work) are made.

We evaluate the algorithm outputs for an *ideal* initialization ("Ideal S-TDMA"), in which the minimum number of slots is reused after every terminal has finished its network entry procedure. We define the *Offered Channel Load* (OCL) as the ratio between the number of slots required by the N_t users, each transmitting r packets per frame, and the number N of available slots: $OCL = N_t \cdot r/N$. In the ideal scenario, if $OCL \leq 1$ no slots is ever being reused. On the other hand, if $OCL > 1$ the SOD after the first frame phases $\boldsymbol{\pi}^{(ff)}$ is:

$$\begin{cases} k = \lfloor N_t \cdot r/N \rfloor \\ \pi_{k+1}^{(ff)} = N_t \cdot r/N - \lfloor N_t \cdot r/N \rfloor \\ \pi_k^{(ff)} = 1 - \pi_{k+1}^{(ff)} \\ \pi_j^{(ff)} = 0 \qquad \forall j \neq k \vee j \neq k+1 \end{cases}$$

For the timeout counter value, we consider two scenarios:

a) the extended values $t_{min} = 1$ and $t_{max} = 10^5$;
b) the standard [8] values $t_{min} = 3$ and $t_{max} = 7$.

Case a) is meant to reduce the spurious collisions due to simultaneous allocation of the same slot by multiple users. This phenomenon particularly affects our model due to the hypothesis of lack of knowledge of the concurrent reservation patterns. By comparing the values of a) with those obtained in scenario b) we can evaluate the impact of this phenomenon.

A. Slot Occupation Distribution

We compute the SOD for a system with $N = 860$ slots/frame, a value very close to the 859 slots/frame established in [2] for 800 bytes CAMs, that allows us to obtain exactly $OCL = 50\%$ with 43 users and a report rate of 10 packets/s, and $OCL = 100\%$ with the same 43 users transmitting 20 packets/s. In both cases $w_{CSmin} = 1$.

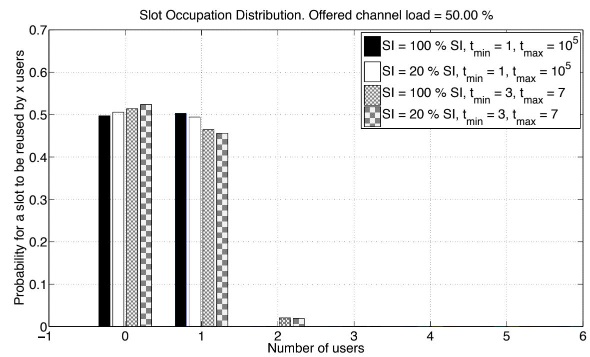

Fig. 4. SOD for OCL = 50%: $N = 860$, $N_t = 43$, $r = 10$

In Fig. 4 can observe that for low OCL, the algorithm describes quite well the expected behavior of the protocol. The size of the SI has little influence, since enough free slots are available in the CS for both configuration. When the standard timeout values are used, a small probability of slot reuse by 2 users is observed, due to the effect of simultaneous reservations of the same slot by multiple users.

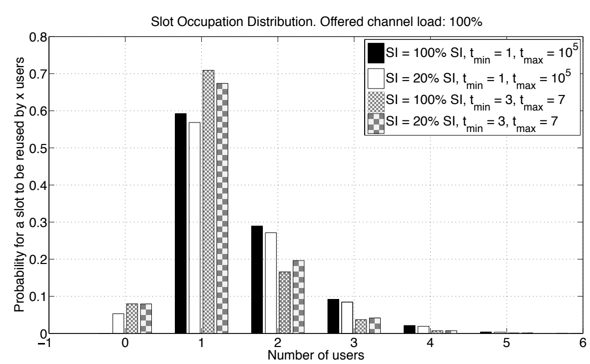

Fig. 5. SOD for OCL = 100%: $N = 860$, $N_t = 43$, $r = 20$

In Fig. 5, the same scenario is evaluated for $OCL = 100\%$. In this case, we can observe that the output of the algorithm is less close to the ideal expected value of $\pi_1 = 1$, $\pi_i = 0, i \neq 1$. This behavior can be attributed to the stochastic algorithm modeling a deterministic phenomenon. In this specific scenario, we can observe how the SOD for standard timeout values provides the closest results to the expected behavior.

This is due to the way the probability for a slot to be sensed free is computed in (10). A larger timeout counter range reduces the occurrences of simultaneous reservation by reducing the probability of a departure event $\pi_{t,1}$. As a side effect, the algorithm is less efficient in capturing the free slots left by the sporadic departures.

It is worth noting that an endless reservation scenario can be obtained by setting $t_{min} = t_{max} \to \infty$. In this scenario, we obtain $\pi_{t,1} = 0$, which substituted in (6), then in (7) and in (2), provides a transition probability matrix $\mathbf{P}$ equal to the identity matrix. In such a scenario, re-reservation is not observed, and slots that are in a given state at the end of the first frame phase keep remaining in the same state.

B. Packet Level Incoordination

In this section, we show the PLI in terms of its complementary, the Packet Level Coordination, or $(1 - PLI)$, the probability for one user not to have one transmission slot reused by other terminals. This metric is evaluated for timeout scenario a) in Fig. 6 and for scenario b) in Fig. 7. In both cases, we consider $N_t = 43$ users, with report rates spanning from $r = 1$ to $r = 40$ packets/s to obtain increasing values of OCL.

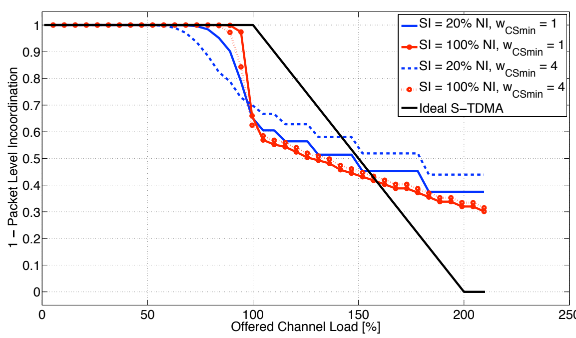

Fig. 6. Packet Level Coordination for $t_{min} = 1$ and $t_{max} = 10^5$

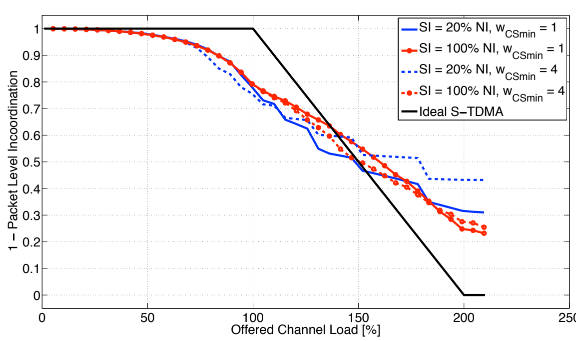

Fig. 7. Packet Level Coordination for $t_{min} = 3$ and $t_{max} = 7$

We can observe that the configuration with extended timeout counter range offers results closer to the ideal curve for $OCL \leq 100\%$, but then it tends to diverge from it for higher OCL values. On the other hand, the configuration with the standard values diverges from the expected curve earlier, but then, for higher OCL, the difference is lower. This behavior can again be attributed to the computation of the probability for a slot to be sensed free, which cannot efficiently capture the slots left free by re-reserving users in highly loaded scenarios.

The curves obtained for wider values of the minimum candidate set size w_{CSmin} introduce further impairment for higher OCL: this is originated by the allocated slots that have to be included in the CS, which can be chosen with equal probability than the already scarce free slots.

VI. Conclusion and Future Works

In this work, we presented the first analytical model of S-TDMA, and provided an asymptotic evaluation of its communication performance in closed form. Despite the abstractions necessary to achieve tractability, the model shows to be closely reproducing the performances of S-TDMA in terms of Packet Level Incoordination. For channel load lower than 50% the model matches the performances of S-TDMA in an ideal channel. For channel load between 50% and 100%, it represents a lower bound, as tight as 5% when considering a 70% channel load. Only in extremely loaded scenarios, the stochastic nature of the model shows its limitations in capturing the deterministic behavior of S-TDMA. A more detailed analysis of the protocol's properties that characterize its behavior under heavy load, along with the comparison with simulation results, is therefore envisioned as future work.

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References

[1] K. Sjöberg, "Medium access control for vehicular ad hoc networks," Ph.D. dissertation, Chalmers University of Technology, 2013.

[2] ETSI, "TR 102 861 Intelligent Transport Systems (ITS); STDMA Recommended Parameters and Settings for Cooperative ITS; Access Layer Part," ETSI, Tech. Rep., January 2012.

[3] A. Alonso and C. Mecklenbrauker, "Stabilization Time Comparison of CSMA and Self-Organizing TDMA for Different Channel Loads in VANETs," in *ITS Telecommunications (ITST), 2012 12th International Conference on*, Nov 2012, pp. 300–305.

[4] K. Bilstrup, E. Uhlemann, and E. Strom, "Scalability Issues of the MAC Methods STDMA and CSMA of IEEE 802.11p When Used in VANETs," in *Communications Workshops (ICC), 2010 IEEE International Conference on*, May 2010, pp. 1–5.

[5] T. Gaugel, J. Mittag, H. Hartenstein, S. Papanastasiou, and E. G. Strom, "In-depth Analysis and Evaluation of Self-Organizing TDMA," in *Vehicular Networking Conference (VNC), IEEE*, 2013, pp. 79–86.

[6] T. Gaugel, J. Mittag, H. Hartenstein, and E. G. Strom, "Understanding differences in MAC performance," *A World of Wireless, Mobile and Multimedia Networks (WoWMoM), 2014 IEEE 15th International Symposium on*, pp. 1–6, 2014.

[7] G. Yang, J. Zhou, and P. Luo, "Slot Collision Probability Analysis of STDMA VHF Data Link," in *Information and Automation, 2008. ICIA 2008. International Conference on*, June 2008, pp. 1723–1727.

[8] ITU, *Rec. M.1371-5 - Technical characteristics for an automatic identification system using time-division multiple access in the VHF maritime mobile band.* International Telecommunications Union, Feb. 2014.

[9] Eurocontrol, "Vhf digital mode 4," Eurocontrol, Tech. Rep. [Online]. Available: http://www.eurocontrol.int/services/ vhf-digital-mode-4

[10] K. Sjoberg, E. Uhlemann, and E. Strom, "How Severe is the Hidden Terminal Problem in VANETs when Using CSMA and STDMA?" in *Vehicular Technology Conference (VTC Fall), IEEE*, Sep. 2011, pp. 1–5.