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Challenging Vehicular Scenarios for Self-Organizing Time Division Multiple Access

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***Abstract*—IEEE 802.11p and the European profile standard ITS-G5 define adjustments to the Physical Layer (PHY) and Medium Access Control (MAC) of IEEE 802.11 for the support of Intelligent Transport Systems (ITS). This includes *ad hoc* communication links between vehicles as well as between vehicles and roadside infrastructure. The MAC method of 802.11p uses randomized backoff in the case of simultanious access attempts which induces unpredictable communication delays. It is known that such unpredictable delays severely limit the value of safety-related services. The most effective way forward is to design a protocol that suits vehicular traffic and safety-related service constraints. Self-organizing Time Division Multiple Access (STDMA) is a suitable alternative. Due to its predictable delay and periodic character, it is suitable for scheduling time-triggered data, such as Cooperative Awareness Messages (CAM). In this article we outline new scenarios for STDMA, which will be the foundation for further simulations and analysis.**

I. Introduction

Cooperative vehicular systems enables new applications to be developed where data is exchanged wirelessly. In a cooperative system nodes provide each other with information, such as safety warnings and traffic information. This can be used in order to avoid accidents and traffic congestions. The cooperation between vehicles for enhancing road traffic safety and efficiency will in many cases use vehicular *ad hoc* networks (VANETs), where all nodes are peers, vehicles as well as roadside units (RSUs). The *ad hoc* topology implies that there is no central coordination in the system such as a base station or access point controlling the network resources.

There has been extensive work on standardization to define a communication standard for Intelligent Transport Systems (ITS) operating in the 5.9 GHz frequency band. In June 2010, the IEEE 802.11p [1] was ratified, which is an amendment to the IEEE 802.11 wireless local area network (WLAN) standard. The major difference between the legacy 802.11 and 802.11p is the removal of the access point functionality in the latter. 802.11p uses carrier sense multiple access with collision avoidance (CSMA/CA) as medium access control (MAC) with support for quality of service (QoS) through 802.11e. The physical (PHY) layer of 802.11p, orthogonal frequency division multiplexing (OFDM), is inherited from 802.11a with the major difference that the frequency channel bandwidth is narrowed down to 10 MHz in 802.11p. In Europe a profile standard of IEEE 802.11p has been approved by the European Telecommunication Standards Institute (ETSI), called ITS-G5 [2].

New kind of applications such as e-safety, traffic management, enhanced driver comfort and vehicle maintenance applications, lead to new communication scenarios in vehicular environments. Road traffic safety applications are the ones with the strongest requirements on the communication. For example sending *emergency notifications* requires a low channel access delay, in order to notify relevant receivers in time to avoid for example collisions; for *risk anticipation* the key feature is predictable channel access delay. Vehicles are monitored so abnormal behaviours can be detected and any change on the cadence of the data traffic must be tracked. ETSI has defined two types of messages for safety-related applications, namely cooperative awareness messages (CAM) [3] and decentralized environmental notification messages (DENM) [4]. CAMs are broadcasted periodically and contain position, speed, heading of the vehicle, they are time-triggered and always present. DENMs, on the other hand, are event-driven and will be triggered when a dangerous situation is about to happen. Both message types require predictability, whereas CAMs have modest reliability requirements as it is repeated periodically and DENMs have high reliability requirements. By predictability is meant that the MAC layers should have a known maximum delay, such that a message can be delivered to the receiver before a predefined deadline. The MAC layer protocol for scheduling safety-related data traffic must be predictable, self-organizing and support both event-driven and time-triggered data traffic.

CSMA/CA of 802.11p provides low channel access delay given that the channel is sensed idle. If the channel is busy, a node waits a random time until it attempts to access the channel again. This random amount of time is calculated via the exponential backoff algorithm. The main drawbacks of CSMA/CA when scheduling safety-related data are: the stochastic nature of the exponential backoff which makes CSMA/CA (*i*) *unpredictable* as the maximum delay is unbounded and (*ii*) *causes simultanious co-located transmissions* when two nodes select the same backoff value which leads to collisions and a degradation of the reception performance and finally (*iii*) *blocking*, which means that as long as the node senses the channel busy, it keeps waiting and never gets to transmit.

A potential remedy to the problems experienced with CSMA/CA could be to use self-organizing time division multiple access (STDMA) [5], where access to the channel always can be provided, regardless of the channel occupancy. STDMA has a periodic structure, where the channel is divided in timeslots, and further grouped into frames. These features are translated into predictable channel access delay, low probability of simultanious co-located transmissions, non-blocking and better ability for scheduling periodic traffic. For these reasons, STDMA is a suitable alternative for managing safety-related data traffic. However, it requires CAMs to be present in the system since the scheduling of transmission slots is based on position information. STDMA has earlier been compared to CSMA/CA ([6][7]) through simulation of a highway scenario where only the time-triggered CAMs have been present. The results show that STDMA is very suitable for VANETs and when the network load increases STDMA outperforms CSMA/CA.

In this article we outline new scenarios for STDMA, which will be the foundation for further simulations and analysis of STDMA. DENMs are event-driven and will be transmitted in case of an upcoming hazard. STDMA is suitable for scheduling time-triggered data, however how does it perform when scheduling DENMs? Nodes using STDMA self-organize and re-organize slot allocations continously to cope with the rapid network topology changes that exist in the vehicular environment. But, what happens if two clusters of STDMA nodes meet? How long does it take before nodes re-organize due to sudden appearance of new nodes?

II. Self-Organizing TDMA

The original algorithm is found in the so-called Automatic Identification System (AIS) [5], a maritime standard. As before mentioned in Section I, the predictability of STDMA originates in its deterministic TDMA [8] approach compared to the probabilistic CSMA/CA approach. In STDMA the time domain is divided into timeslots, where a message fully occupies one timeslot.

When an STDMA node joins a VANET, it enters the **initialization phase**, where it listens to the activity of the channel during one frame to perceive the slot allocation from other STDMA nodes. Then it defines the amount of messages that is going to be transmitted during the frame, *N*, in other words the heartbeat rate (HB) in Hz (the frame size is *S* seconds). There is predefined number of slots in each frame, *M*.

After the **initialization phase** the node enters the **network entry phase**. This is the phase when the node introduces itself to the VANET by determining the first transmission slot and use it. First, in this phase the size nominal increment (NI) l_{NI} is decided. There are the same number of NIs in the frame as messages that the node wants to transmit, N. The NI is found by dividing M/N and is the amount of timeslots that will elapse on average between the allocated slots in the frame. The first transmission slot is decided by first randomly picking one slot from the current slot, i, up to $i + l_{NI}$. This slot will be called the nominal start slot (NSS). Around NSS is a selection interval (SI) of slots defined, which is 20% of the slots found in NI. The SI is put around NSS with NSS being the slot in the center of SI. Within SI the node will once again choose a slot randomly, which will be the nominal transmission slot (NTS). If the chosen NTS is occupied by someone else the node will search through the SI until a free slot is found. The slot assignment during the **network entry phase** is shown in Fig.1.

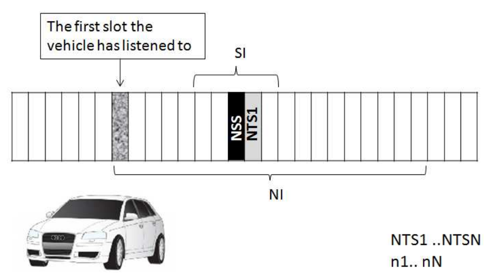

Fig. 1. STDMA slot assignment for network entry phase.

When the first NTS is used for transmission the node enters the **first frame phase**. During the **first frame phase** the rest of the transmissions slots are decided. Next step is to add NI slots to NSS and this new slot will be called nominal slot (NS) instead of NSS. This is to distinguish where the first entrance in the frame was made by this particular node. Every node has its own frame start to achieve a high randomness between nodes. Then determining the second transmission slot is done by putting the SI around NS and randomly picking a transmission slot, NTS, within this SI. For the third transmission slot, NI slots are added to the current NS and the SI is put around the NS and a new NTS is found in the SI. The procedure of determining all transmission slots is repeated until all the desired slots have been allocated in the frame. The slot assignment during the **first frame phase** is shown in Fig.2.

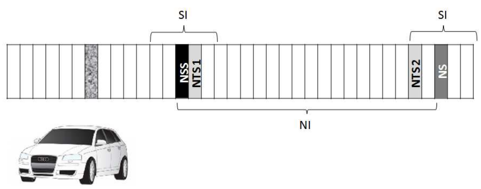

Fig. 2. STDMA slot assignment for first frame phase.

Finally, when all the timeslots within one frame duration are selected, the node will enter **continuous operation**, using the NTS decided previously for transmission. Each NTS has got a reuse factor n, associated to it which defines for how many frames this particular NTS is going to be used by this node. When$n$ expires the node randomly selects another NTS out of the available ones within the SI and attaches a new n as a random integer within $3..7$. If all slots happen to be occupied, the node selects a NTS occupied by a node located furthest away from itself. This is why with STDMA channel access is always ensured, but it also makes STDMA dependent on the fact that there is position information available at the MAC layer such as CAMs in order to select NTS based on location when all slots within SI are occupied. This makes the algorithm especially suitable for VANETs where many applications are dependent on position information, such as CAMs which will be broadcasted by every vehicle.

III. Messages for Safety-Related Applications: CAM and DENM

The proposed communication architecture in Europe contains a facility layer ([9] [10]) shown in Fig.3. The facility layer is situated between the application layer and the network and transport layers. It provides support to the applications and is divided into three entities: *application support*, *information support* and *communication support*. The *information support* is comparable to the presentation layer of the OSI model, whereas the *communication support* is the tantamount to the session layer of the OSI model. The latter offers different communication modes requested by the applications such as broadcast, unicast, geocast etc. The *information support* manages all the remote data received from other vehicles and RSUs as well as the data generated by the own vehicle. All data is contained in a database called the Local Dymanic Map (LDM). ETSI has defined two kinds of messages for safety-related applications - CAMs and DENMs. These messages will be used to update the LDM of each vehicle with the information acquired from the rest of the nodes of the network. The generation of CAMs and DENMs is done in the *application support* upon application requests (see Fig.3).

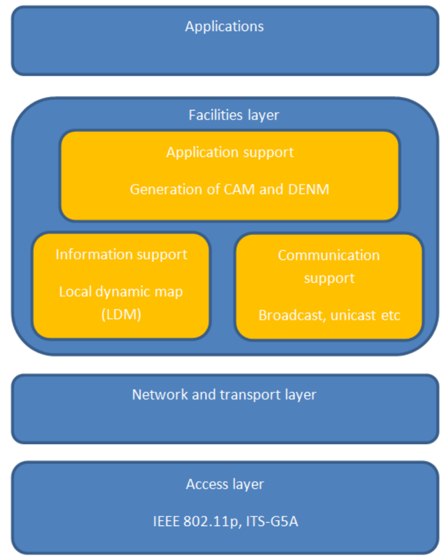

Fig. 3. Facilities Layer Architecture

CAMs are broadcasted periodically by every vehicle in the VANET with a constant data rate of 6 Mb/s. The heartbeat will be from 1 Hz up to 10 Hz and the packet size will be around 800 bytes, depending on the settings. They convey information about the vehicle transmitting such as position, speed, heading, sensor data etc. As these messages are sent periodically, the status of each node on the road is continuously updated. All data is stored in the LDM. All vehicles shall be able to generate, send and receive CAMs, as long as they participate in vehicle-to-RSU/vehicle (V2X) networks, i.e., it is mandatory to support CAMs in Europe. By receiving CAMs, the vehicle is aware of other vehicles in its neighbourhood area, as well as of their positions, movement, basic attributes and basic sensor information. This allows vehicles to get information about its situation and act accordingly. Two proposed applications that are utilizing CAMs are; the approaching emergency vehicle and slow vehicle warning.

DENMs contain information about a certain type of event taking place within a region, so its content is type of event and region of event. They are mainly used by the application cooperative road hazard warning (RHW) to alert road users of the detected events. They are triggered in case of a hazard and are continuosly broadcasted until the hazard is no longer apparent or avoided. Accidents or traffic jam warnings can be sent by means of these messages. A DENM provides information related to an event that has a potential impact on road safety, such as event type, geographical position or area, the detection time and a duration. These attributes may change over space and over time. Furthermore, a DENM can be used for traffic efficiency such as the dissemination of a DENM over a long distance or to a central road traffic management center via RSU and can be used for rerouting road traffic. A DENM, which concerns the same event, may be issued by multiple originator (vehicles) at different positions and persists even after the originators (vehicles) have passed by. Therefore, the detected event can be independent from the originator vehicles. Furthermore, the reliability of the provided information related to the same event may vary at different originator vehicles, depending on the detection capability of that vehicle.

IV. Scenario Description

The vehicular scenarios that have been studied so far in order to evaluate the performance of STDMA have been highway scenarios where few new nodes turned up every frame. The entrance of new nodes were smooth and the nodes easily adapted to the current slot allocations. The work [6] was conducted for a saturated network and the results show that STDMA outperforms CSMA/CA in terms of packet dropping at the transmitter (none in the STDMA case) and successful channel access in comparison to CSMA/CA nodes. The contribution [7] was conducted comparing STDMA with CSMA/CA of IEEE802.11p for a network that is not saturated. In such networks it was proven that STDMA outperforms CSMA/CA also when considering performance metric such as the distance between concurrently transmitting nodes.

There are still other challenging scenarios for STDMA, such as those where two clusters of STDMA nodes join or where two data traffic types (CAM and DENM) are forced to cohabitate. It is also interesting to evaluate the performance of STDMA in saturated networks during the start-up phase of the network, thus when many nodes are in **initialization**, **network entry** and **first frame phase**, at the same time. This section describes three challenging vehicular scenarios for STDMA and carries out the discussion of each one.

A. Start-up phase of a VANET

It is already shown that STDMA behaves properly when a couple of new nodes are turned on every second. If there already are nodes in the system, which has a certain amount of allocated slots in the STDMA frame, the action of joining the STDMA frame is smooth and not very controversial since the nodes must listen to the frame once before starting to allocate slots. However, what happens if many nodes within radio range are turned on during one frame duration? And also what happens if many nodes are turned on during consecutive frames?

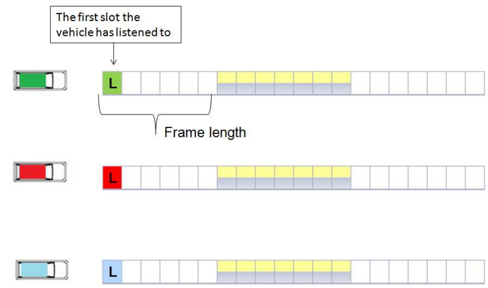

Fig. 4. Several vehicles turned on during one frame duration might attempt to gain the same NTS due to the same perception of the frame (unintended slot reuse)

This can occur at a parking lot located outside a stadium, where, after a major event, many people will pick up their cars and start them approximately at the same time. There will be CAM messages present in the VANET as soon as the vehicles are turned on (see Fig.4).

In such a scenario there are two use cases to be analyzed: when the newborn VANET is *(i) saturated* and *(ii) not saturated*.

i. *Saturated*: In this scenario there will be more vehicles requesting resources than available timeslots. All nodes will allocate timeslots regardless of the number of nodes within radio range. When their SIs are fully booked with other nodes they will transmit at the same time as someone else at the parking lot (intended slot reuse). This scenario will probably create strong interference amongst the overlapping radio ranges of a great number of nodes resulting in poor packet reception probability.

ii. *Not saturated*: In this scenario there will be less requested resources than available slots. For this use case it is interesting to see how long it takes before all nodes have found their NTS because nodes will allocate the same slot due to the same perception of the frame in the beginning (unintended slot reuse). It is interesting to determine how many frames it takes before STDMA has organized itself and no unintended slot reuse is present for different data traffic loads.

CSMA as MAC method typically have less trouble with (*ii*) because when there are fewer nodes than resources available, the majority of all nodes will gain channel access as long as the attempts do not all come at the same time (chosing the same backoff value). However in (*i*) when the network load increases nodes will drop packets at the sender before they are even transmitted (blocked).

Interesting performance indicators in the STDMA case are e.g., the reuse factor of slots (when the network load is high) and packet reception probability within different ranges from the transmitters. In order to test such a scenario, the following parameters have to be set-up:

a. Number or vehicles in the parking lot
b. Rate with which they appear (e.g., all nodes come during the same frame preferably Poisson distributed)
c. CAM rate and packet size

The network load can be increased either by increasing the number of vehicles or by increasing the CAM rate or/and message size. This leads to an open question: Is there any difference in the behavior if the load is increased in either of the two ways?

B. Two STDMA clusters merging

Every node in an STDMA system has its own perception of the frame allocation and everyone has its own frame start (there are as many different frame start options as slots in the frame). Hence, nodes are slot synchronized but not frame synchronized. Nodes that are in the same geographical area will perceive approximately the same slot allocations in their respective frames. Further, they will also be organized and unintended slot reuse is unlikely in unsaturated situations. The situation with co-located nodes, cluster of nodes, can be found for example when vehicles travel in the same direction on a highway. But what happens if a cluster, called A, travelling in one direction meets another cluster, called B, merging onto the same road? Cluster A is well-organized internally, i.e., all nodes have found transmission slots without interfering with each other and then cluster B suddenly turns up, also well-organized internally. How long will it take before cluster A and cluster B have reorganized and created a new ”common” perception of the frame and concurrent transmissions (using the same timeslot as a node located close by) are diminishing? Within the cluster, all the neighbour nodes are scheduled and do not experience any kind of collisions, but as soon as the two clusters begin to merge it might happen that vehicles from Cluster A have the same NTS as other cars from Cluster B (see Fig.5). As long as their reuse factor does not expire, they will keep on transmitting and packet collisions will occur.

The amount of collisions depends on:

- *The amount of vehicles in both clusters*: The higher the channel load of each cluster, the less the timeslot availability and thus the higher the collision probability amongst vehicles belonging to different clusters.
- *Each vehicles reuse factor when merging process begins*: Collision keep happening as long as the reuse factors of colliding NTS do not expire. The larger reuse factor is, the greater the number of collisions.

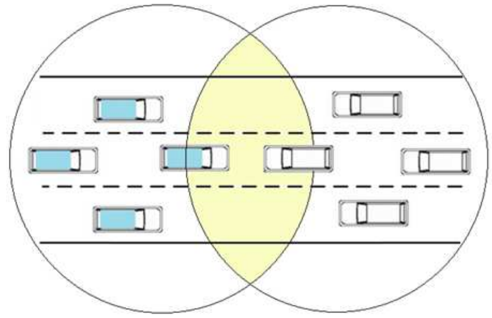

Fig. 5. As soon as the two clusters begin to merge it might happen that vehicles from Cluster A have the same NTS as other cars from Cluster B. In this scenario packet collisions will occur.

The vehicles on the lead position of the cluster (the ones situated in front of the cluster), could inform the neighbours as they sense collisions, so the rest assign their reuse factors a lower value, such that they expire as soon as possible. To test such a scenario, the following parameters have to be set-up:

a. Number of vehicles in cluster B
b. CAM rate and packet size;
c. Rate with which nodes from cluster A appear

C. Emergency vehicle approaching a traffic jam

STDMA has a predictable delay and guaranteed channel access, also in saturated scenarios when using CAMs. The predictable delay is very useful for risk anticipation applications. CAMs are pre-scheduled and are perfectly suited for STDMA. In VANETs supporting road traffic safety applications, the MAC method must also support event-driven data traffic, i.e., DENMs. This scenario will describe the possibility to support DENMs and study how CAM traffic and DENM traffic cohabitate, and whether this is a source of many concurrent transmissions.

The scenario chosen is the same as in [11], namely a highway scenario where an emergency vehicle is approaching a traffic jam. The purpose with this application is to let the emergency vehicle more easily pass through the traffic jam, which means reduction of time for the emergency vehicle to arrive at its destination. All vehicles within the traffic jam must receive the messages from the emergency vehicle to act on them. In the original AIS standard there is an access method called random access TDMA (RATDMA), where nodes occasionally can choose to send in a slot which is random selected among all slots in the SI that are perceived as free, e.g., one message every 10th frame. It is clear that after sensing the hazard, action must be taken as soon as possible. As the CAMs are already scheduled in the frame, the DENM channel access delay will depend on the following:

- *Slot assignment mechanism for DENM*: The assigned timeslot is randomly selected from the available timeslots within the selection interval. If the hazard is sensed just before the assigned timeslot occurs, the vehicle can broadcast the emergency rapidly. But if it has just passed, the vehicle will have to wait until the next selection interval to transmit.
- *Heartbeat rate*: If the heartbeat rate is higher, the selection intervals will be smaller and in case of having missed the opportunity of broadcasting the hazard in the previous assigned timeslot, the time to be wait for transmitting in the next one will be lower.

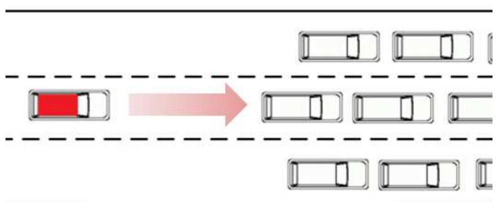

Fig. 6. A emergency vehicle broadcasting DENM messages is approaching a traffic jam where vehicles keep broadcasting CAM messages

A single node rapidly entering an area of very high node density is an issue of particular concern in VANET communications. In such a scenario the packet reception probability can be evaluated for different distances to the traffic jam. For testing such a scenario, the following parameters have to be set-up:

a. Number or vehicles in the traffic jam
b. CAM rate and packet size
c. DENM rate and packet size
d. Time when the emergency vehicle appears and its speed

V. Summary

The current 802.11p MAC method is based on a probabilistic approach and does not guarantee upper bounds on the message delay, which is a key feature for safety-related applications. STDMA is very suitable for VANETs and when the network load increases it outperforms CSMA/CA, by providing channel access regardless of the channel occupancy. Moreover, it provides a predictable delay and minimizes simultanious transmissions from co-located nodes.

ETSI has already standardized CAM and DENM as formats for safety-related messages in vehicular communication scenarios. Even though CAMs are broadcasted periodically whereas DENMs are event-triggered, predictable channel access are crucial for both types of messages. STDMA appears to be suitable for scheduling CAM data traffic. However, until now its performance has only been evaluated for time-triggered data traffic in highway scenarios.

In this article we have described new challenging scenarios for STDMA, which will be the foundation for further simulations and analysis of this protocol. For each scenario a description and the tunable parameters have been provided. Issues such as the performance of STDMA during the start-up phase of a VANET, the interaction between two STDMA clusters merging and the cohabitation of CAM and DENM traffic have been presented and discussed. The next step will be implementing each scenario and presenting the performance results.

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