Throughput of Self-Organizing Time Division Multiple Access MAC Layer for Vehicular Networks based on measured SNR time-series

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***Abstract*—IEEE802.11p is an approved amendment to the IEEE802.11 standard providing wireless access in vehicular environments (WAVE). It defines enhancements to the Physical layer (PHY) and Medium Access Control (MAC) for the support of Intelligent Transport Systems (ITS). This includes communication links between vehicles as well as between vehicles and a roadside infrastructure. The current MAC method uses randomized backoff in the case of access collisions which induces upredictable 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 and can coexist with the current IEEE802.11p MAC method. Self-Organizing Time Division Multiple Access (STDMA) is a suitable alternative, due to its structured channel access, predictable delay and periodic character.**

This contribution presents the time-evolution of throughput based on measured signal-to-noise ratio time-series of four vehicles driving on the same road joining the channel. These time-series were acquired during a real-world experiment in the 5.9 GHz band during 2010. Our results show that a collision-free access featuring predictable communication delay is feasible.

I. Introduction

Vehicle manufacturers in cooperation with road and infrastructure operators from North America, Europe, Japan and Australia (among others) are working towards a common standard for vehicular communications for future Intelligent Transport Systems (ITS). Such ITS will provide a safer and more comfortable driving from the user point of view. From another perspective thank to this protocol road operators are going to be able to manage the traffic so that congestions and road accidents are significantly reduced.

The approved amendment defines enhancements to the 802.11 standard required to support ITS applications. This includes data exchange between high-speed vehicles and between the vehicles and the RSUs in the licensed ITS band of 5.9 GHz. There has been much research done so far in the field of vehicular channel characterization [1]–[3]. Due to the fact that IEEE 802.11p [4] and the European profile standard ITS-G5A [5] are both wireless LAN (WLAN) technology-based approaches for automotive use, they implement the 802.11e Medium Access Control (MAC) layer variant, which is not best suited for services with strong restrictions on latency and delay, such as protective and accident avoidance applications. The exponential back-off implemented by the Enhanced Distributed Channel Access (EDCA) in 802.11e-compliant devices shows open issues involving the difficulties on performing optimization procedures in order to provide minimum delay and high probability of delivery for safety-related messages.

To overcome limitations given by the mobile environment, [6] proposes an extension of the current method for improved Quality of Service (QoS). [7] presents a secure MAC protocol for vehicular ad hoc networks (VANETs) with different message priorities for different types of applications, focusing more its effort on improving security and data integrity rather than in time critical message delivery. It is in [8], where a deeper study of the delays introduced by the actual IEEE802.11p MAC layer protocol is carried out. Results show how analyzing the delay dependencies on different loads (in Mbps) is a matter of interest. All the solutions and studies presented so far, have worked with collision avoidance medium access algorithms, where nodes adopt a handshaking approach before sending messages. In 2009 the work of [9] took Time Division Multiple Access (TDMA) into account, as another possible collision avoidance MAC method for vehicular environments. TDMA [10] is a technique where the timeline is split into a series of the time periods, and each period is divided into a set of time slots. Each car is then assigned a slot in which it transmits its messages every period. As vehicular networks have a dynamic topology, the slot assignment must be validated as changes happen, in order to keep the MAC layer protocol mobility-aware. Reference [11] also presents another TDMA solution for roadside unit (RSU)-to-vehicle communication. This approach consists of a sublayer to be on-top of the conventional IEEE802.11p MAC. The solution presented shows to be plausible for RSU-to-vehicle communication scenarios but not in a car-to-car communication context, where the extension of the coverage area is not as important as a predictable low delay on the transmissions.

Motivated by the results shown in [9] and [12], a more detailed study on the Self-Organizing TDMA (STDMA) MAC method has been carried out by our group. In this paper we present a STDMA model designed and simulated using Stateflow state charts [13] and Simulink block diagrams [14], applications based on Mathworks tools [15].

The contributions of this paper are: (a) the definition of the STDMA MAC Layer controller and the whole simulation environment so vehicular communication scenarios can be studied, and (b) analysis using Matlab and Simulink.

The rest of the paper is organized as follows: In section 2, we discuss the main reasons why we believe that developing a new MAC layer for emergency operations where urgency and protectiveness are required on vehicular communications is a better option rather than adapting the existing solution. In the following section the STDMA protocol and the STDMA model are described, by means of system architecture and operation of the protocol itself. Finally in section 4 results are shown from an example environment and section 5 presents summary and outlook.

II. Open issues for the IEEE802.11p MAC Layer Protocol

In the standard ISO network model, the MAC layer is responsible for managing local communication, providing the higher layers with a reliable local communication service [16]. In case of WLAN the MAC protocol coordinates the transmission using CSMA/CA as fundamental access. Carrier sensing algorithms are very effective when the medium is not heavily loaded, since it allows users to transmit with a minimum delay. However, there is always a chance of several users transmitting at the same time (i.e. collision), because the users sensed the medium free and decided to transmit at once. CSMA/CA reduces the collision probability by virtual carrier sense mechanism, exponential back-off procedure, Inter Frame Space (IFS) and RTS/CTS mechanism. Nevertheless, it shows some deficiencies, such as the fairness problem [17] and the hidden node problem [18].

In case of VANET, the MAC protocol will not only have to have a minimum delay but also a predictable delay, as this will be a key feature for accident avoidance applications. In order to anticipate to an accident situation or to monitor the traffic to react to an emergency the information must be spread in an intelligent and efficient way. Therefore there are two types of messages standardized by the European Telecommunication Standards Institute (ETSI)for safety-related applications:

- *Cooperative Awareness Messages (CAM)* [19]: These messages convey information such as type of vehicle, position, speed and heading. They are broadcasted by each car every 100 ms at a constant data rate. Their goal is to provide the rest of the users a virtual map of their neighbours on the road and some additional information so they can be informed about the current state of the traffic. As these messages are sent periodically, the status of each node on the road is continuously updated.
- *Decentralized Environmental Notification Messages (DENM)* [20]: These messages contain information about a certain type of event taking place in a region (so its content is type of event and region of event). They are broadcasted by the RSU or by a vehicle.

  Accidents or traffic jam warnings can be sent by means of these messages.

As all the vehicles will broadcast the above mentioned messages at the same rate the fairness of CSMA/CA will not be a problem anymore. But the hidden node problem still remains, and thus collision can still happen.

A concrete implementation of the MAC layer algorithm over a radio model implies delay statistics. Safety applications in vehicular networks must fit very low and foreseeable delay constraints. Due to this hidden node problem and the random nature of the exponential back-off, it is a better solution to find an alternative, which improves the overall system performance. The real challenge is finding a MAC layer protocol which outperforms the actual in critical message scheduling with a predictable delay but still can coexist with the 802.11e EDCA. Coexistence is the key for both cases: either for providing a smooth transition from one protocol to the other in the case one proofs to be the best solution for all purposes; or in the case that the new approach only beats the existing one in safety-related data traffic management, for granting non mutual interference while operating for different use cases.

III. Model Implementation

We implement the Self-Organizing Time Division Multiple Access (STDMA) [9] which offers the advantage of predictability for safety applications in VANETs. The original algorithm is to be found in the so-called Automatic Identification System (AIS) [21], a maritime standard. The predictability of STDMA originates in its deterministic TDMA approach rather than the probabilistic CSMA/CA approach.

In STDMA the time domain is divided into time slots, where a message fully occupies one time slot. In contrast to other self-organizing TDMA schemes, STDMA has a structured access channel for slot assignment.

The nodes in STDMA listen to the channel during one frame and they select free slots for transmitting their data. If there are no free slots, a node chooses to send in an occupied slot, used by the farthest away situated node. This capability is suitable for the CAM service implementation, as each CAM message records position, to be used by the MAC layer. The nodes are synchronized in terms of heartbeat rate but each node starts transmitting at a different time within the frame. When a node is turned on, it follows four different states, shown in Fig. 1: (i) initialization, (ii) network entry, (iii) first frame and (iv) continuous operation. During (i) the node listens for the channel activity amongst one frame (called superframe) to determine the frame structure. Within this time it records the messages of the active nodes transmitting, containing position of each of them. In (ii), the node selects its own slot based on the information acquired previously. If all the slots are occupied, the node will make use of the position knowledge to transmit in the slot of the farthest node. In (iii) the node begins transmitting in the slot decided in (ii), joining the network actively for the first time. The last phase (iv) is when the node falls into continuous operation, transmitting periodically messages in the slot assigned before.

Still, as topology changes in the network, the slot allocation should change dynamically. Thus, during (iii) the node draws a random integer (n in the Fig. 1) for each slot assignment, which determines for how many consecutive frames this particular slot will be used [12].

One major advantage of STDMA, appart from the predictable delay, is that it can coexist with the actual IEEE802.11p MAC protocol. Suposing a vehicular environment where the two systems handle CAM traffic: CSMA/CA nodes will be sensing the channel continuously and only transmiting when it is free, whereas STDMA nodes will sense the channel only for gathering their time slot, and then will transmit continuously during their assigned time slot. But system compatibility is a different issue and it does not work so straightforwardly. As far as there are free time slots left, there will be no problem, but when the superframe is full, a newcomer CSMA/CA node will sense that the channel is busy and will keep waiting, whereas a newcomer STDMA node will need to calculate its furthest away node to gain its time slot. For this calculation the incoming vehicle will need the GPS coordinates and the n indicator of every car of the network. This requires CSMA/CA nodes to add this information to their MAC layer frame and update the n value for every CAM message they transmit.

The event driven system model is implemented via Matlab's Simulink and Stateflow block sets. This choice of implementation was selected because it enables automatic translation into executable code on target hardware platforms. We have designed blocks that specifically help STDMA modeling such as Network Traffic Generator, Vehicle Node and CAM Traffic Generator. The *Network Traffic Generator* contains mainly an event-based entity generator that reproduces packets of

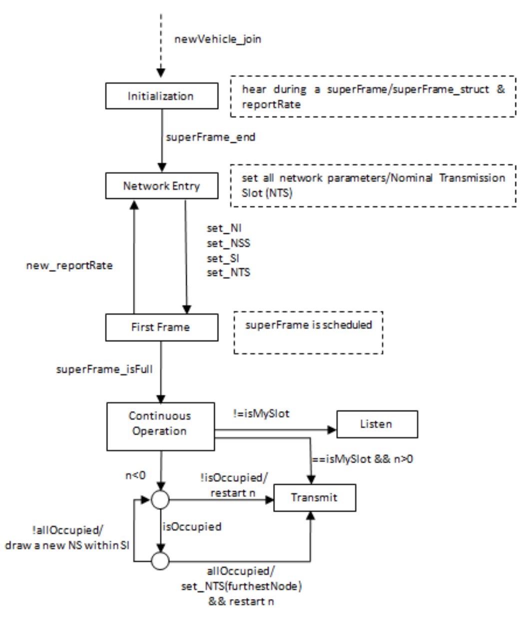

Fig. 1. STDMA algorithm implemented

a configurable size and transmits them periodically. These packets are composed of configurable attributes (packet size, communication delay, position). The *Vehicle Node* encompasses the *CAM Traffic Generator*, which after the first frame structure, will begin generating packets at heartbeat rate. *Vehicle Node* also takes in a parameterized Stateflow block which actually implements the algorithm running inside each single node. The Stateflow chart is a library object and each vehicle holds a MAC layer controller which takes in an instance of it. Therefore, every node of the framework is running an independent copy of the same algorithm.

Although many network simulation tools exist (e.g. NS-2 [22], Qualnet [23] and OMNET++ [24]), we evaluate the MAC layer performance directly in Simulink to avoid the required interfacing between diverse tools. We use the following simple PHY layer abstraction for the throughput analysis. We consider a packet as an indivisible unit as in [25]. The packet error probability is modeled by the frame error ratio at time t for the kth vehicle-to-vehicle link (0s$\leq t \leq$9s and $k = 1, \dots, 4$) which we idealized by

$$\mathrm{FER}_k(t) = \begin{cases} 0, & \text{if } \mathrm{SNR}_k(t) > \mathrm{SNR}_{\mathrm{threshold}}, \\ 1, \text{else.} & \end{cases} \quad (1)$$

A packet is thus received succesfully if the signal-to-noise ratio (SNR) is higher than the pre-defined threshold $\mathrm{SNR}_{\mathrm{threshold}}$ where we assume that collisions do not occur. STDMA is a collision-free protocol and the channel access is always provided. If all the slots are occupied, the vehicle willing to access the channel will calculate which is its furthest away node, and will wait until this furthest away node has sent all its frames (i.e. wait until its n indicator expires), and the begin transmitting in its timeslot. Based on [26], we set $\mathrm{SNR}_{\mathrm{threshold}} = 15\,\mathrm{dB}$ for the parameters in Table I. Thus, we model the kth vehicle-to-vehicle link behaviour by a time-series $\mathrm{SNR}_k(t)$ which we sampled during the ROADSAFE measurement campaign, which took place in September 2010. The car-to-car experiments were carried out in a two-lane tunnel scenario and each measurement run was 9-10s long.

IV. Results

In this section we present results for two different scenarios. The simulation parameters used are shown in Table I. In a VANET where each superframe has got a transfer rate of 3 Mbps, each car transmits 500 byte long messages every 100 ms and there can cohabitate up to 75 vehicles within 1s superframe.

TABLE I
Parameter Setting for Simulation

Parameter	**Value**
Transfer Rate, R	3 Mbps
Heartbeat Rate, H	10 Hz
Packet Size, N	500 byte
Superframe Period	1 s

Fig. 2 shows results for a single vehicle transmitting in a VANET. This simulation has been carried out to test the functionality of the model. The car senses channel activity and after listening to the SF structure it begins transmitting in its messages. The slot assignment is done by calculating the nominal transmission slot (NTS) for each CAM message within a SF. For H = 10 Hz, there will be 10 NTS values per SF. Each of them is randomly selected from the selection interval (SI), which is a subarray from the SF structure, and has got its own n indicator (1..7), which defines for how many SF the vehicle is going to have this slot reserved for its use. So the vehicle will listen to the SF, note which time slots are free and then will randomly select from each SI a NTS to transmit out of the available time slots.

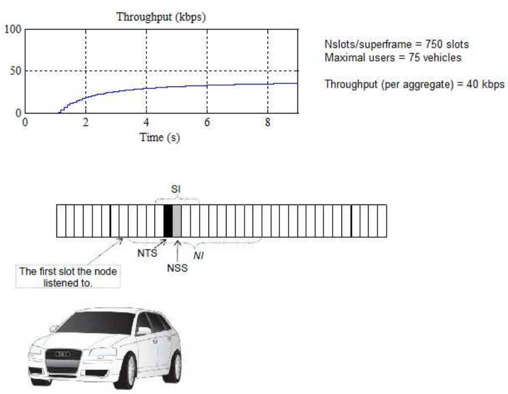

Fig. 2. Throughput and slot assignment for Vehicle1

The figure above depicts the traffic in kbps that a of a single aggregate sends to the channel. Now we calculate from this value the total throughput for the 75 possible aggregates transmitting in a full traffic scenario and we obtain the expected 3 Mbps throughput.

Fig. 3 shows results for a more complex and realistic scenario based on the ROADSAFE measurement campaign data. It presents the time evolution of the channel state as four cars enter the network at different time instants. The simulation scenario consists of one reference car driving in a tunnel, while at different time instants other vehicles are going to enter its coverage area, overtake it and finally leave the coverage area. When each vehicle enters the initialization state (Vehicle 1 at 0 s, Vehicle2 at 1 s,Vehicle3 at 2 s and Vehicle4 at 3 s). Channel state in Fig. 3 reassures that STDMA is collision-free, as expected.

The throughput analysis in this realistic context is now done from the point of view of a reference car that senses and processes the data traffic of channel. This car listens to the channel for a SF, then waits until the superframe life expires and listens to the channel again, so it will sense the channel periodically. This period will be defined by the superframe life, which in our case is 2, so the throughput will be analyzed at 2 s, 4 s, 6 s and 8 s. For high mobility scenarios, where the cars are driving fast and the propagation environment changes rapidly, a short superframe life would be more suitable so

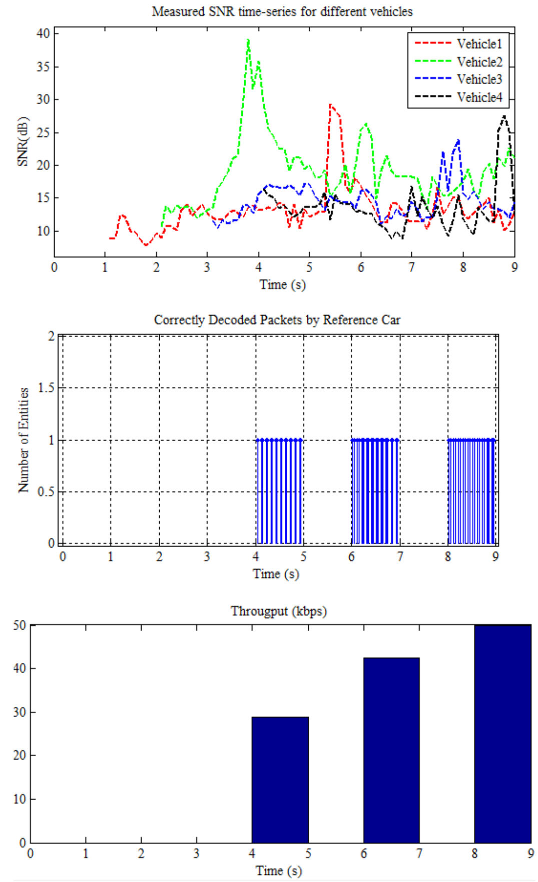

Fig. 3. Channel structure, Measured SNR time-series for different vehicles, Correctly Decoded Packets and Throughput for a car driving along in the scenario

the car can sense the changes on the road as fast as they are happening. Whereas for high traffic density scenarios, where the environment is constant and the variation slow, this parameter can be diminished, as changes will not happen so quickly. After applying the physical layer abstraction described in section 3, we see that in Fig. 3 at 2 s the SNR level of the sensed packets transmitted by Vehicle1 and Vehicle2 is lower that the SNR threshold defined by the reference car and that is why no correctly decoded packets or throughput is accounted at this point. But from 4 s to 5 s there are some correctly decoded packets and throughput increases to 28.93 kbps. Then it will be zero until it listens to the channel again and processes the new traffic. In this specific scenario the throughput obtained within 4 s and 5 s is generated from two vehicles transmitting, the throughput obtained within 6 s and 7 s is generated from three vehicles transmitting and the last one within 8 s and 9 s from all the vehicles tranmitting.

V. Conclusions

The current 802.11p MAC method is based on a probabilistic approach and does not guarantee upper bounds on the message delay. Future safety-related applications and infotainment services vastly differ in their requirements for message delay and link reliability. Therefore, a future enhanced 802.11p

MAC layer needs to satisfy these vastly differing requirements while coexisting with legacy MAC methods.

ETSI has already standardized CAM and DENM as formats for safety-related messages in vehicular communication scenarios. Even though CAM messages are broadcasted periodically whereas DENM messages are event-triggered, low delays are crucial for both types of messages. Due to the collision-free operation and its structured channel access, STDMA is a suitable alternative for scheduling CAM traffic. Moreover, STDMA turns out to be suitable for coexisting with the 802.11e MAC layer variant.

We have carried out STDMA simulations using measurement samples from SNR time series collected during the ROADSAFE 2010 measurement campaign. The results show how four vehicles actively join the network at different time instants. The vehicles deterministically select the time slot for transmission based on the information acquired when receiving the first frame. Next, they start transmitting CAM messages periodically without collisions.

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