Towards Real-Time Media Access in Vehicular Ad-Hoc Networks

Steffen Moser, Jochen Weiß and Frank Slomka
Institute of Embedded Systems/Real-Time Systems
Faculty of Engineering and Computer Science
Ulm University, 89069 Ulm, Germany
E-Mail: {steffen.moser | frank.slomka}@uni-ulm.de, jochen.weiss82@googlemail.com

***Abstract*—By giving vehicles the ability to propagate warning messages to the other ones, the number and the severity of accidents on our streets could likely be reduced. Safety-related applications based on vehicular ad-hoc neworks (VANET) are usually dependent on transmitting a message from source to sink within a given time limit. IEEE proposes the standard 802.11p which is an adaption of the well-known Wireless LAN 802.11a for inter-vehicle communication. While many properties have been improved, 802.11p still comes with a contention-based medium access control, only. This leads to an indeterminism and data-dependencies. One deterministic and fairer alternative compared to contention based medium access mechanism would be Time-Divison Multiple Access (TDMA). As a VANET is typically fully self-organizing, the time slots must be assigned autonomously by the nodes of the distributed system. This, however, leads to drawbacks in the performance of the protoctol which are analyzed in this paper.**

I. Introduction

Inter-vehicle communication has been seen as one approach to decrease as well the amount as the impacts of accidents on our streets. Typical applications are vehicles being able to propagate warning messages about dangerous street conditions like suddenly appearing ice or oil to other vehicles, but also an extension of a driver's range of sight would be possible. This can be interesting, for example, at badly visible intersections or at hidden ends of traffic jams.

Also non-safety related applications are imaginable, for example achieving a smarter routing of vehicle traffic to reduce the number of congestions on heavily loaded streets. This kind of an advanced route guidance system would allow saving of both, energy and time. A possibility to accomplish this would be by gathering information about traffic load and exchanging this information with other cars and infrastructure components.

One of the most actively researched approaches to implement car-to-car communication are wireless ad-hoc networks. In contrary to established cellular networks typically used for mobile voice and data communications, wireless ad-hoc network allow inter-vehicle communication without the need of infrastructure for network organization purposes. The nodes of the network organize themselves spontaneously. Applied to vehicle communication, mobile ad-hoc networks are mostly called vehicular ad-hoc networks (VANETs). In contrary to other ad-hoc network applications, VANETs can be characterized by their very dynamic behavior, which results in fluctuating communication channel properties and a highly time-variant network topology. This makes the self-organization of VANETs even more challenging.

Nodes of a VANET necessarily share a common resource: the communication channel. This leads to the focus of this paper. When multiple nodes share a common communication channel, there must be channel access control mechanisms, typically called the medium access control layer (MAC). Various MAC mechanisms exist with different properties, for example, deterministic and non-deterministic or centralised and decentralized ones.

In June of 2010, the 802.11 working group of IEEE published the standard 802.11p for VANET communication [1]. 802.11p is based on the well-established 802.11a wireless LAN standard. Various regulatory authorities have reserved frequency spectrums in the 5.9 GHz band for dedicated short-range communications (DSRC) in the area of vehicle-to-vehicle and vehicle-to-infrastructure communication in the meantime. The MAC mechanism used by 802.11p is in principle the same that is used by other protocols of the family (e.g. 802.11a, 802.11g or 802.11n). It is designed as a Carrier Sense Multiple Access method with Collision Avoidance (CSMA/CA). CSMA/CA can be classified a decentralized contention-based medium access algorithm.

As mentioned above, VANETs are seen as a communication technology for safety-related applications. Many of them need to respond within given time intervals, so, for example, the warning of a traffic jam's end in a blind bend is only useful when the message is received fast enough to give the drivers of the following vehicles enough time to react and brake. As CSMA/CA is a competitive MAC method, it is not possible to give any real-time guarantees in advance, but only statistic predictions regarding the maximum transmission time for a message. Depending on the application to be developed, this can be insufficient for the application designer in the field of automotive engineering.

For the given reasons, we evaluate different approaches on the MAC layer. Besides CSMA/CA, variants of a Self-Organizing Time Division Multiple Access (often abbreviated as S-TDMA or SO-TDMA) can be interesting for VANET communication.

This paper is structured as follows: In the next section the basics of VANET communication are presented, for example the typical network load scenarios, medium access control protocols and the related work is discussed. In the third section we present our approach to compare different medium access protocols. Thereby our simulation setup is given. While the fourth section is used to present and discuss our simulation results, we conclude with the fifth section by summarizing the results and giving an outlook of further research that will be done.

II. Communication and Medium Access in VANETs

A. Characteristic Channel Utilization in VANETs

The network traffic caused by projected future applications in VANETs can be described as follows:

- Non-Safety-Critical, aperiodic network traffic like information exchange for route guidance systems, updates of maps or other multi-media data.
- Safety-Critical, aperiodic network traffic like emergency messages, e.g. warnings about danger zones on the street or a sudden obstacle.
- Periodically sent beaconing messages, also called Cooperative Awareness Messages (CAM). These messages contain information about position, speed and further information and are sent by all vehicles to announce their presence to the environmental vehicles. A lot of applications are based on CAM, also safety-critical ones (e.g. visibility extension at crossroads). The typically proposed frequency of sending out beacons is 10 Hz [2].

Undoubtedly, the safety-critical messages should be transmitted with a higher priority than the non-safety-critical ones. IEEE 802.11p comes with the ability to assign different priorities to various kinds of messages. However, as stated above, IEEE 802.11p doesn't provide any maximum time interval which has to be waited for a message being actually sent.

To allow a fair comparison of different medium access approaches, we derive real-time constraints from the CAM frequency of 10 Hz in this paper without loss of generality. This means that in our case a beaconing message has to be sent out within 100 ms. The reason is that after 100 ms a new beaconing message will be created containing updated information about the vehicle's state. So the old CAM would be outdated and useless for the application after this amount of time. In vehicle applications the real-time constraints and the CAM frequency would have to be rather derived from the physical state of the vehicle, e.g. its speed.

B. Competitive Medium Access

IEEE 802.11 based protocols use CSMA/CA as the MAC method. A network node in the ready-to-transmit state waits and at the same time checks for a specific amount of time if the channel is free. The amount of time is dependent on the priority of the message. If the channel stays free for the whole time of checking, the node starts to transmit. In the case that another node gets active during the waiting and checking phase, a back-off process with a randomly chosen amount of time is started. This behavior of each node listening to the channel and beginning to send when it is considered as free, leads to the highly load-dependent behavior of the medium access time.

C. Time-Division Multiple Access (TDMA)

The idea of TDMA is that each network node gets its own sub-interval of time of a larger frame. This means, each node in the network will get access to the channel periodically. Time-Division Multiple Access is used, for example, by the Global System for Mobile Communications (GSM) or Digital Enhanced Cordless Telecommunications (DECT). These applications differ from VANETs in one important aspect: In contrast to VANETs, the nodes of a GSM or DECT system have a management link to a base station. This means the base station is able to assign unique time slots to each node which can be accessed without the chance of getting collisions. The fact that each network node has its unique time slot together with knowing the amount and length of time slots offers the possibility to derive the maximum time a node has to wait for channel access.

D. Self-Organizing Time-Division Multiple Access (S-TDMA)

Assigning time slots to network nodes is usually the task of a distinguished master node or a base station. In a highly dynamic vehicular ad-hoc network, such a base station is not available. Therefore, a decentralized algorithm has to be used to manage the distribution of the time slots. The algorithm for self-organization which has been analyzed in this paper is an adaption of the one presented by Bilstrup et al in [3]. It is based on the medium access method which is used for a ship-based collision detection system, called Automatic Identification System (AIS). For in-depth information about AIS and its properties, see [4]. The presented idea of S-TDMA requires access to a common time source. This can be achieved by connecting a GPS receiver to each node of the ad-hoc network. Intermittend of the GPS signal, for example in inner-city scenarios due to buildings, and aspects of drifting local clocks are not considered here. Although used in a typically fast-changing environment, it is also necessary for each node to learn about its neighbor nodes. This means: Whenever a network node gets active, it has to listen at least for one complete TDMA frame for the time slots which used by a neighbor node. One of the unused time slots is chosen then by the newly activated node. Afterwards the newly activated node begins to send out periodic beaconing messages as stated in section II-A. Here, these beaconing messages get an additional function: In the concept of S-TDMA, they are used to mark the busy time slots in the neighborhood. Starting or arriving nodes can then use this information to find their own slots. This step of listening to the channel and choosing a time slot, which does not seem to be in use by another vehicle, introduces a problem which is uncommon for the typical usage of regular infrastructure-based TDMA: Due to the mobility of the nodes, it happens that two or more nodes share a time slot. This can cause severe collisions.

E. Other Multi-User Medium Access Approaches

There are also further approaches besides CSMA and TDMA to achieve a multi-user medium access in an ad-hoc network. For example, Code-Division Multiple Access (CDMA) is a method which allows multiple nodes to use the communication channel simultaneously at the same radio frequency. The messages from various nodes are distinguished at the receivers' ends by a redundant pseudo-random sequence which the messages are spreaded with. On the one hand, this is quite a promising approach for real-time medium access because it allows network nodes to send out a message immediately – without doing any synchronization at all. Especially one would not have to wait for a free channel (CSMA) or for the assigned time slot (TDMA), but it introduces two problems in VANETs on the other hand:

1) The signal power received from different nodes can vary a lot. This is due to different behavior of the communication channel between a sender and a receiver node. The distance and the presence of obstacles is crucial. A closed-loop control of the transmit power is impossible in broadcast oder geocast scenarios which are typical for VANET scenarios. This problem is known as the near-far problem. Its influence on ad-hoc networks is analyzed in detail by Muqattash et al [5].
2) The signal processing which has to be done for CDMA is more complex compared to the one needed for CSMA/CA or TDMA. As proven by existing products which make use of CDMA, this is not a problem for today's signal-processing integrated circuits anymore, but the models and utilities used to describe and simulate VANETs neglect the signal-processing done by the physical layer completely. In the majority of today's VANET simulations, the situation of two or more simultaneously transmitting nodes within a specified spatial region is simply considered as a collision without having a closer look at the physical layer and the actual abilities of decoding a mixture of signals [6]. This makes it very challenging to do simulation-based research about CDMA in VANETs.

Due to these unsolved problems with CDMA, we will focus on CSMA versus Self-Organizing TDMA and their real-time behavior in this paper.

F. Related Work

Wireless ad-hoc networks have been a wide-spread matter of research. A lot of groups focus on questions of multi-hop routing algorithms, aggregation of information, communication security and privacy issues. Most of the research work in the upper layers like routing or aggregation is done by using the CSMA/CA based medium access control as proposed by the IEEE, only few groups acutally question the applicability of CSMA/CA based methods.

In [3] Bilstrup et al. showed that they have been able to construct a channel load caused by using beacon messages sent out by a specific number of vehicles per area which can render an application useless, because the necessary beacon messages cannot be sent before their expiration (assumed 100 ms). They propose a self-organizing TDMA approach as an alternative for applications with real-time constraints. While the real-time aspects and comparisons between IEEE 802.11p and self-organizing TDMA are discussed very extensively, the effects of collisions in self-organizing TDMA networks are not considered explicitly. As the self-organization process is non-deterministic itself in a short period of time, it is possible that two or more nodes share a time-slot. Depending on their distances to the receiver and the received signal strengths, this can lead to a collision. A better comparison is given in [7].

Stanica et al. [8] use also the self-organizing TDMA setup proposed by Bilstrup et al. While they also consider the loss of packets due to collisions, they only send out beacon packets in intervals of 500 ms, but not in higher frequencies. Another drawback is that they permanently use the maximum transmit power of 33 dBm which is the maximum that is allowed in Europe [1]. This results in very large ranges of coverage which are not needed for a lot of applications operating in a very local area where a few hundred meters are typical. Working with a too high transmit power loads the communication channel unnecessarily and therefore lowers the number of possible nodes.

TABLE I
DIFFERENT PARAMETERS BETWEEN IEEE 802.11A AND 802.11P

Parameter	802.11a	802.11p
Bit rate (Mbit/s)	6, 9, 12, 18, 24, 36, 48, 54	3, 4.5, 6, 9, 12, 18, 24, 27
Duration of symbol	4 μs	8 μs
Guard time	0.8 μs	1.6 μs
Duration of preamble	16 μs	32 μs
aPLCP Header Length	4 μs	8 μs
aSlot Time	9 μs	13 μs
aSIFS Time	16 μs	32 μs

TABLE II
GENERAL SIMULATION PARAMETERS

Parameter	Value
Simulated Time	180 s
Mobility Model	Highway Scenario
	4 km length, 2 directions
	3 lanes per direction
	Speed on right lane: 70 - 90 km/h
	Speed on middle lane: 90 - 110 km/h
	Speed on left lane: 110 - 130 km/h
Channel Model	Stochastic
	Two-Ray Ground Pathloss
	Rayleigh Fading
Number of Vehicles	100 / 1000
Packet Size	260 Byte
Beaconing Frequency	10 Hz

III. CSMA/CA VERSUS S-TDMA

We would like to find out if and in how far S-TDMA is able to outperform CSMA/CA regarding its real-time behavior. Do study this, we have set up the following simulations:

- Simulation of a highway mobility scenario using the network simulator JiST/SWANS (developed by Barr et al [9]). More detailed information about the simulation parameters is given in Table II. The highway scenario is a very simple model of a plain road with 6 lanes, 3 of them in each direction and different average speeds on the lines. This has been set up due to the fact that the very simple radio propagation models which are part of JiST/SWANS have only an influence on the real radio channel behavior on a free space without any obstacles like buildings. This has been shown extensively in [10] and [11].
  JiST/SWANS also does not provide the IEEE 802.11p specific parameters. Therefore we extended JiST/SWANS as stated in Table I by a modified MAC layer and a physical layer which are able to consider the different parameters of 802.11p.
- Simulation of the same highway mobility scneario but using S-TDMA on the MAC layer of the communication system instead of IEEE 802.11p. The implementation is based on [3].

Two aspects have been objects of research: The first one is the question how the MAC layer influences the time needed to access the channel. Therefore, we simulated two load scenarios: 100 and 1000 vehicles with both MAC layers. The second aspect is the question of collisions. As stated above, S-TDMA has an indeterministic phase, too. This means that it is possible that a node which has been started up gets a time slot which is in use by another node. This will lead to a collision and render the radio communication useless for the time of overlapping.

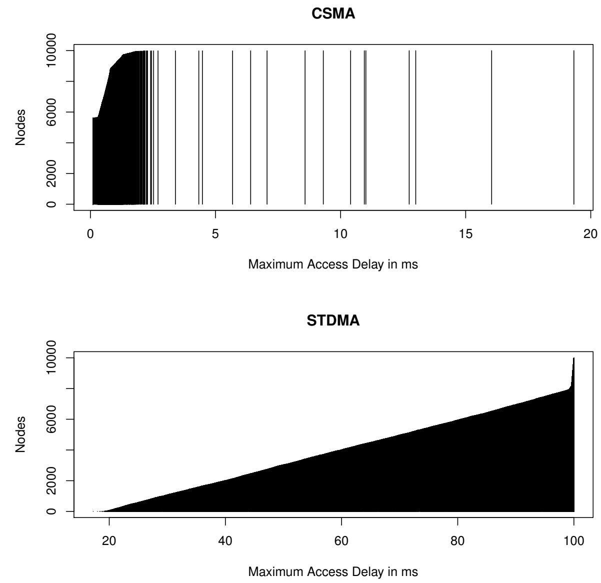

Fig. 1. Maximum time needed for channel access in 100 vehicles scenario

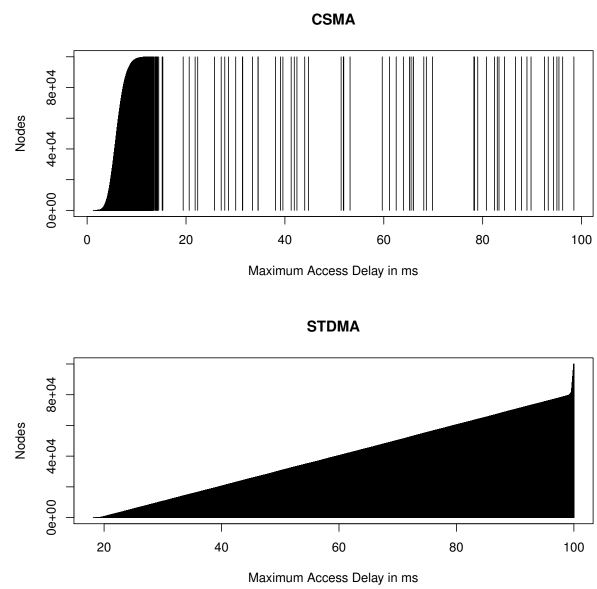

Fig. 2. Maximum time needed for channel access in 1000 vehicles scenario

IV. SIMULATION RESULTS

A. Maximum Channel Access Delay

In the first step, we measured how different MAC models influence the maximum time which is needed to get access to the communications channel. This is depicted in Figure 1 for a scenario with 100 vehicles and in Figure 2 for a scenario containing 1000 vehicles. As we executed the simulation more than 100 times to get statistically stable results, the accumulated number of nodes in the graphs are much higher.

S-TDMA is parametrized in both scenarios (100 and 1000 vehicles) in a way so that all nodes can get channel access within 100 ms. The distribution of the channel access times is caused by the time a node has to wait until its time slot occurs. As these times are equally distributed, the graph looks like expected. For the scenario with 100 vehicles CSMA/CA performs much better than S-TDMA. Even for the scenario with much higher load (1000 vehicles), CSMA/CA needs less time to wait for channel access than S-TDMA. Our simulations also gave notice that we can expect deadline violations (i.e. channel access times larger than 100 ms) for CSMA/CA when the number of vehicles per area further increases.

B. Reception Probability

We also studied the reception probability as a function of the distance between sender and receiver. The maximum distance we considered was within the distance where the signal is powerful enough to be received and decoded. This means that the reception probability can be seen as an indicator for the number of packets which are dropped due to collisions.

The reception rates for CSMA/CA and S-TDMA for both,

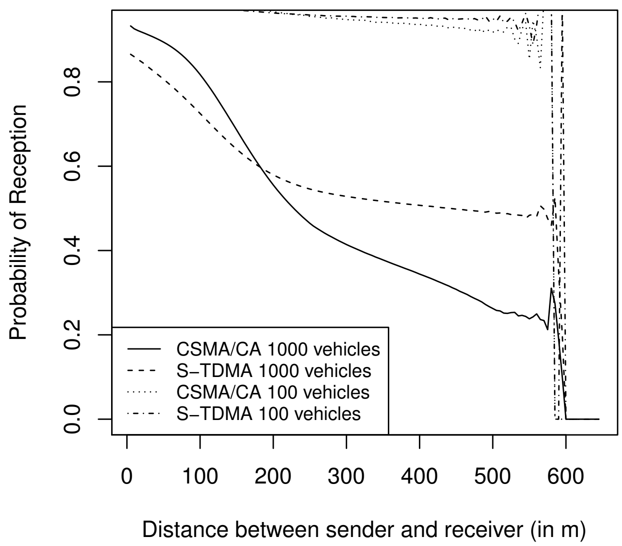

Fig. 3. Reception probability as a function of distance.

the 100 and 1000 vehicles scenario are depicted in Figure 3.

While for the 100 vehicles scenario the reception rate was quite high for all distances, in the 1000 vehicles scenario a clear break even between CSMA/CA and S-TDMA can be seen. When sending messages to near neighbors, CSMA/CA seems to perform better than S-TDMA. As a lot of safety-critical applications rely on communication in the direct network neighborhood, we cannot recommend S-TDMA without reservation.

V. Conclusion and Future Work

In this paper we have implemented and studied the behavior of different medium access control schemes in larger-scale vehicular ad-hoc network simulations. While CSMA/CA, which is part of the standard proposed by the IEEE, does not offer any real-time guarantees, we have encountered that it performs better than the more deterministic S-TDMA. The latter is able to outperform CSMA/CA only for a very high density of vehicles.

In future work we will integrate our more realistic radio channel model into out VANET simulation framework. This will allow us to consider inner-city scenarios much more realisticly. Especially the fast-changing channel behavior in cities could be even more challenging for the organization phase of S-TDMA.

We also plan to continue the research in the field of CDMA in ad-hoc networks as an alternative for highest-priority messages.

References

[1] Working Group, IEEE 802.11p, "IEEE Standard for Information technology - Telecommunications and Information Exchange between Systems – Local and Metropolitan Area Networks – Specific Requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 6: Wireless Access in Vehicular Environments." Tech. Rep., June 2010.

[2] E. M. van Eenennaam, G. Karagiannis, and G. J. Heijenk, "Towards scalable beaconing in vanets," in *Fourth ERCIM workshop on eMobility*. Luleå University of Technology, Luleå, Sweden, May 2010, pp. 103–108.

[3] K. Bilstrup, E. Uhlemann, E. G. Ström, and U. Bilstrup, "On the Ability of the 802.11p MAC Method and STDMA to Support Real-Time Vehicle-to-Vehicle Communication," in *EURASIP Journal on Wireless Communications and Networking vol. 2009, Article ID 902414*, 2009. [Online]. Available: http://downloads.hindawi.com/journals/wcn/2009/902414.pdf

[4] "Recommendations ITU-R M.1371-1, Technical characteristics for universal shipborne automatic identification system using time division multiple access in the VHF maritime mobile band," Tech. Rep., April 2001.

[5] A. Muqattash and M. Krunz, "CDMA-based MAC Protocol for Wireless Ad Hoc Networks," in *Proceedings of the 4th ACM International Symposium on Mobile Ad Hoc Networking & Computing*, ser. MobiHoc '03. New York, NY, USA: ACM, 2003, pp. 153–164. [Online]. Available: http://doi.acm.org/10.1145/778415.778434

[6] S. Moser and F. Slomka, "Towards more Realistic Simulations of Ad-hoc Networks - Challenges and Opportunities," in *Proceedings of the International Symposium on Performance Evaluation of Computer and Telecommunication Systems (SPECTS)*, Juli 2010.

[7] K. Bilstrup, E. Uhlemann, and E. Ström, "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.

[8] R. Stanica, E. Chaput, and A.-L. Beylot, "Comparison of CSMA and TDMA for a Heartbeat VANET Application," in *Communications (ICC), 2010 IEEE International Conference on*, May 2010, pp. 1 – 5.

[9] R. Barr, "An Efficient, Unifying Approach to Simulation Using Virtual Machines," Ph.D. dissertation, Cornell University, 2004. [Online]. Available: http://jist.ece.cornell.edu/docs/040517-thesis.pdf

[10] S. Moser, F. Kargl, and A. Keller, "Interactive Realistic Simulation of Wireless Networks," in *Proceedings of the IEEE/EG Symposium on Interactive Ray Tracing 2007*, 2007.

[11] I. Stepanov and K. Rothermel, "On the impact of a more realistic physical layer on manet simulations results," *Ad Hoc Netw.*, vol. 6, pp. 61–78, January 2008. [Online]. Available: http://dl.acm.org/citation.cfm?id=1293378.1293656