Time-Critical Data Delivery for Emergency Applications in Vehicle-to-Vehicle Communication

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***Abstract*—Transmission of time-critical messages in accident situations is of paramount importance for safety applications in VANET. These messages always require very low latency, which is an important metric for these applications. In particular, they impose real-time requirements. The MAC layer is an important place to satisfy multitude of performance metrics and can be greatly exploited to achieve low latency. In this paper, we exploit the existing VeMAC protocol and modify its TDMA frame structure to improve its performance for time-critical emergency traffic. We introduce additional emergency slots for transmission of emergency messages so that vehicles with time-critical emergency messages do not have to wait for their turn for transmission of such messages. The modified version of the VeMAC protocol results in improved performance for transmission of emergency traffic. The proposed protocol is evaluated through simulations. The results show great improvements and achieve lower latency in different scenarios.**

Index Terms*—*Vehicular Ad-hoc Network* (VANET); *Vehicle-to-Vehicle* (V2V) *Communication*; *Medium Access Control* (MAC); *Time-Critical Traffic*; *Emergency Applications

I. INTRODUCTION

The transmission of time-critical emergency traffic in Vehicle-to-Vehicle (V2V) network is imperative to safeguard safety of drivers and passengers, in this regard an emergency optimized Medium Access Control (MAC) protocol has been proposed in [1]. A Vehicular Ad-hoc Network (VANET) [2], [3] is a network of moving vehicles, where the vehicles, equipped with sufficient sensing, computation, and communication capabilities dynamically form an ad-hoc network without any mandatory infrastructure. The sensing, computation, and communication capabilities are housed into a unit referred to as On Board Unit (OBU). VANETs are a special class of Mobile Ad-hoc Networks (MANETs) [4], but having unique characteristics such as high mobility of nodes, dynamic network topology, varying communication environment, varying number of nodes, varying node distribution.

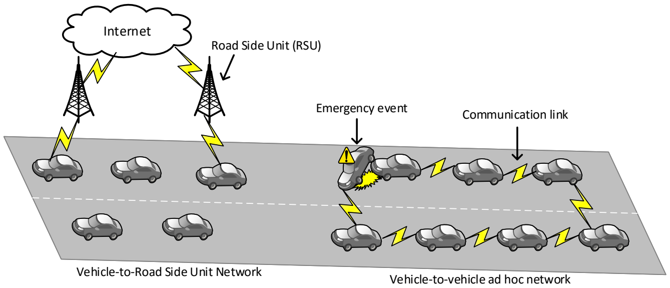


Figure 1. A Vehicular Ad-hoc Network (VANET) showing an emergency event caused by an accident between two vehicles.

VANETs are designed for the purpose to exchange traffic or accidental information between Vehicle-to-Vehicle (V2V) and Vehicle-to-Road Side Unit (V2RSU) or Vehicle-to-Infrastructure (V2I) networks as shown in Figure 1.

The V2V allows the direct communication among vehicles through their OBUs, whereas the V2RSU involves vehicles to communicate with the RSU or vice versa. Generally, the RSUs are simply stationary network nodes that are mounted on traffic lights, street lights, road signs, etc. [5]. The cellular base stations, which are already prevalent can serve as RSUs and can be utilized to support V2RSU communication. An other option may be to use LTE base stations to support V2RSU communication [6].

VANETs have received tremendous attention due to plethora of applications they support such as *intelligent transportation system* (ITS), traffic information dissemination, infotainment, and the Internet connectivity on the go [7] [8]. Among these, the potential application of VANET is ITS, where the core objective is to control accidents, reduce traffic congestion, and improve driving safety in urban areas. Owing to importance of VANETs and the multitude of applications supported by the technology, several efforts were taken to standardize it. Federal Communications Commission (FCC) allocated $75\,\mathrm{MHz}$ spectrum in the $5.9\,\mathrm{GHz}$ band for Dedicated Short-Range Communication (DSRC) [11] solely for the purpose of V2V and V2RSU communication. DSRC is

Table I
LATENCY REQUIREMENTS FOR CERTAIN EMERGENCY SERVICES IN VANETS [9] [10].

Service	Latency requirement
Collision warning	$\leq 100\,\mathrm{ms}$
Pre-crash sensing	$\leq 20\,\mathrm{ms}$
Lane change warning	$\leq 100\,\mathrm{ms}$
Transit vehicle signal priority	$\leq 100\,\mathrm{ms}$

widely recognized as the IEEE 802.11p [12] Wireless Access in Vehicular Environments (WAVE) and is considered the *de-facto* standard for VANETs, it is based on IEEE 802.11 MAC and IEEE 802.11a Physical (PHY) layer [13].

The prime goal of VANETs is to disseminate safety and emergency messages, the timely transmission of such messages is critical to smooth operation of safety applications. The prominent examples of safety and emergency applications are primarily related to road accidents that cause loss of life of the drivers and passengers in vehicles. Other emergency related applications are intersection collisions warning, lane change assistance, overtaking vehicle warning, emergency vehicle warning, pre-crash warning, wrong way driving warning, signal violation warning, hazardous location warning, etc. [14].

In case of an emergency situation such as an accident as depicted in Figure 1, it is imperative to timely communicate such information to nearby vehicles so as to ensure safety of other nearby vehicles. But if such safety message and warning encounter longer delays, it becomes less effective to prevent such accidental situation for nearby vehicles. There is a life-time associated with the safety messages, which requires them to be transmitted timely otherwise they become ineffective. Table I depicts typical latency requirements for various emergency services in VANETs applications.

As latency is an important performance metric for safety/emergency applications and can be controlled through the Medium Access Control (MAC) layer so this requires for efficient medium sharing. Thus, an efficient MAC protocol should ensure high reliability, low end-to-end latency, and high throughput. Therefore, we analyze and exploit the MAC layer in reducing latency for safety/emergency messages in the context of V2V communication.

In this paper, we propose the emergency enhanced VeMAC (EEVeMAC) protocol, which is a variant of the VeMAC [15] protocol. VeMAC is a multichannel Time Division Multiple Access (TDMA) MAC protocol, which is based on ADHOC MAC [16]. The EEVeMAC protocol modifies the slotframe structure of VeMAC and uses emergency slots to transmit time-critical emergency messages in case of road accidents or collisions among vehicles in VANETs. In this way, it targets to meet the real-time requirements of the safety applications. The EEVeMAC achieves low latency for emergency messages under different scenarios and is evaluated by simulation. With reference to our earlier work [1], the main contribution of this work are as follows:

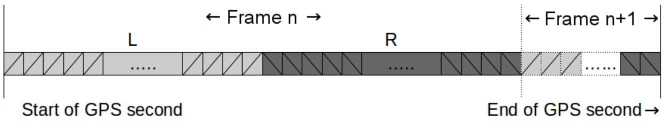
- We extend the EEVeMAC superframe structure to four emergency slots for the transmission of time-critical messages.
- We extensively evaluate the EEVeMAC by simulations with two emergency slots as well as with four emergency slots.
- We demonstrate the protocol in the dense urban scenario, and show how the addition of more emergency slots impact the protocol behavior and latency.
- We analyze the effect of adding more slots on collision rate and compare it with collision rate of two emergency slots.

The remainder of the paper proceeds as follows. In Section II, we give a background overview VeMAC, its working principle, and frame structure. It talks about possible collisions that can occur and explains slot divisions into disjunct sets. We highlight the drawbacks of VeMAC for low latency aspects. Subsequently, Section III gives overview of the desired changes in VeMAC to achieve low latency for transmission of time-critical messages. In Section IV, we describe the evaluation details of our proposed MAC protocol through simulation. We discuss different real life scenarios for which the protocol is evaluated. We also present details of the simulation environment and the associated components that were used to conduct simulations. Section V discusses the results of simulation and shows latency improvements through box plots. The results are presented for various scenarios considered. Finally, a conclusion is drawn in Section VI.

II. BACKGROUND

In this section, we present background details of the VeMAC protocol. We thoroughly explain the VeMAC, its frame structure, and working mechanism.

VeMAC frame structure: VeMAC (no abbreviation) [15] is a multi-channel TDMA protocol for VANETs, which utilizes two radios. One of the radios is always tuned to the control channel c_0, while the other radio can be tuned to one of the service channels. Each node should acquire exactly one slot on the control channel. The node holds onto this slot until it does not need it anymore or until a merging collision occurs. These collisions occur if two nodes, with the same slot, enter the same two-hop-neighborhood due to their mobility. To reduce the number of collisions, the slots are divided into disjunct sets L, R, and F as shown in Figure 2. The frame structure is split in two disjunct sets based on the general direction of movement of the vehicles. If a node travels in general eastern direction, so $0-180°$ degrees of a compass



L = L-Set for left-directional vehicles
R = R-Set for right-directional vehicles

Figure 2. Frame structure of VeMAC protocol [15].

as shown in Figure 3, it would be in the R-subset (colored in dark grey in Figure 2), the rest in the L-subset (colored in light gray in Figure 2). F is an optional set for RSUs, which has no direction of movement. That way, vehicles driving in opposing directions are not competing for the same slot and it reduces the relative speed of nodes competing for the same slots and thereby increases the network topology persistence within these sets.

The directions are provided by the GPS unit that each vehicle is mandatory to be equipped with. With the GPS unit, it is possible to synchronize the frames through the pulse per second (PPS) signal provided by each GPS receiver. A frame should start at the beginning of each GPS second.

The VeMAC protocol proposes a time division in a periodical frame structure of fixed duration. One frame consists of 100 slots, where the length of one slot is of $1\,\mathrm{ms}$ duration, hence a frame length of $100\,\mathrm{ms}$. Each node should transmit periodically one message per frame in its allocated slot. The message consists of a header field, two fields to organize the allocation of slots on the service channels as well as one field for exchange of information for high-priority short applications.

Each node should have a unique random ID to identify the node. The header of the message of node x includes, amongst others, the set $N(x)$, which is the set of IDs of the one-hop neighbors of node x on channel c_0, from which node x has received packets on channel c_0 [15] in the previous 100 slots.

With the sets $N(y)$ of each one-hop neighbor y, the node is able to determine which slots are used by its two-hop neighborhood. These slots, that the node must not use in the next 100 time slots, are denoted by $T_0(x)$. With this information, the node builds the set of available slots $A(x) = \overline{T_0(x)}$ respectively with regard to the directional division, e.g., $A(x) = \overline{T_0(x)} \cap R$ for vehicles driving in eastern direction. These sets are the respective complementary set to $T_0(x)$, a node can use any slot that is not explicitly marked as used by its two-hop neighborhood. With the provided information, the node is able to solve the hidden-terminal problem.

Node x also determines whether or not all of its one-hop neighbors received its last broadcast by looking for its ID in the right slot in all $N(y)$. It thereby constitutes a reliable broadcast mechanism. Due to the regular transmitting, there exists an upper bound for transmission of messages of $100\,\mathrm{ms}$. However, $100\,\mathrm{ms}$ is a long time in high mobility scenarios.

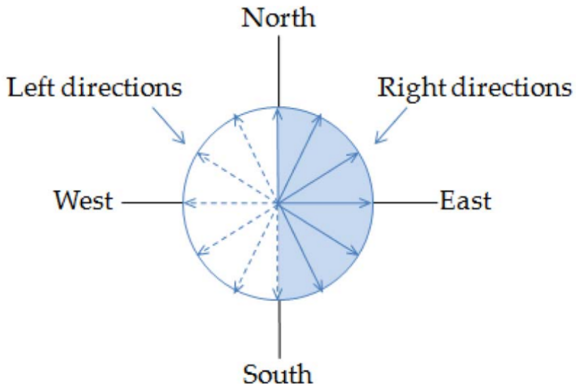


Figure 3. Division of node per direction [15] showing the distinction for the L set and R set. All vehicles driving in $0 - 180°$ degrees of a compass, will be in the R-subset for right directions, the rest in the L-subset for left directions.

Limitation of VeMAC for emergency messages: In $100\,\mathrm{ms}$, a car traveling on the highway with the recommended speed of $130\,\mathrm{km/h}$ already covers a distance of $3.6\,\mathrm{meter}$ and many cars drive considerably faster on the highway in Germany. While the $100\,\mathrm{ms}$ limit should be sufficient in normal use, it might be too long for emergency situations where fast responses are crucial.

III. EMERGENCY ENHANCED VEMAC (EEVEMAC) PROTOCOL

To reduce the latency in emergency situations, in this paper, we propose Emergency Enhanced VeMAC (EEVeMAC), which is the variant of the VeMAC protocol, by introducing emergency slots (colored in orange) at the beginning of the L set in slot 0 and R set in slot 50 as shown in Figure 4. They are evenly distributed across the frame structure to reduce average distance to any other slot. The slots are based on the principle of Carrier Sense Multiple Access (CSMA) for the transmission of time-critical emergency data.

In case of an emergency, a vehicle wants to send time-critical data to notify other vehicles of its situation. In this way, instead of waiting for its next allocated slot, the vehicle can use these additional emergency slots to quickly transmit the messages and avoid catastrophic situations. With additional slots, vehicles have three possible slots instead of one to transmit their data during emergency situations, effectively bringing down the upper bound latency to $50\,\mathrm{ms}$. While the upper bound latency is $50\,\mathrm{ms}$, the median average is further reduced since a slot is able to choose from three possible slots for emergency transmission instead of one.

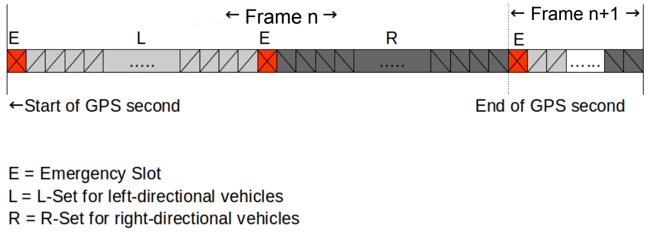


Figure 4. Frame structure of VeMAC with emergency slots. The emergency slots are set at the beginning of the L set respectively the R set.

While the original VeMAC protocol does not define the exact nature of $N(x)$ for node x, we implemented them in both VeMAC and EEVeMAC as pair of ID and slot number to preserve the reliable broadcast mechanism. Through this modification, an ID can be twice in a set. A receiving node then thereby acknowledges the reception of an emergency message by including the ID of the sending node in the emergency slot number in which it received the emergency message. This implementation decision will extend the length of the regular message by a maximum of 100 bytes (88 bits total, 7 bits for representation of numbers up to 128, rounded up to 8, multiplied by 100 slots).

IV. IMPLEMENTATION AND PERFORMANCE EVALUATION

The EEVeMAC protocol is evaluated through simulation in OMNeT++ [17] simulation environment together with Veins [18] and SUMO [19]. Veins is an open source simulation framework for vehicular network simulation. It bidirectionally couples two softwares: OMNeT++ is utilized for network simulation and the open source traffic suite SUMO of the German Aerospace Center provides the traffic simulation data. SUMO has several car-following-models and lane-changing-models to reproduce realistic traffic behavior. Veins integrates MiXiM [20] for modeling physical layer effects and provides realistic interference models. For our simulation we use the two-ray-interference model provided by Veins [21]. The simulation parameters are listed in Table II whereas the scenario parameters are given in Table III.

Scenarios:

Two scenarios "straight" and "interchange" with reduced road traffic and normal road traffic were tested to examine the influence of node numbers on collisions.

Straight and interchange scenarios:

In the straight scenario, only traffic from northern and southern directions was present; in the interchange scenario vehicles started from each direction. The highway interchange Münster south, Germany was created in SUMO as shown in Figure 5 and provided with traffic statistic of the state office for road construction NRW [22] to achieve a realistic traffic

Table II
SIMULATION PARAMETERS

Layer	Parameters	Value
APP	Field size	6000 x 6000 m
	Network	Dynamic
	Number of nodes	Varying number
	Distance between nodes	varying
	Data rate	18 Mbps
PHY	Radio tx output power	20 mW
	Propagation model	Two-ray model
	Frequency spectrum	2.4 GHz
	Sensitivity	−89 dB m
	Thermal noise	−110 dB m
MAC	Frame duration	100 ms
	Slot duration	1 ms

Table III
CONFIGURATION PARAMETERS IN THE TWO SCENARIOS

Parameters	Value	
Scenario	Straight	Interchange
Traffic flow from direction	North/South	North/East/South/West
vehiclesPerHour (total value)	4645	9476
Use of Emergencyslots	False/True	False/True
Emergency in slot	1/25/49	1/25/49
Replications	50	50
Simulation duration	80 sec	80 sec

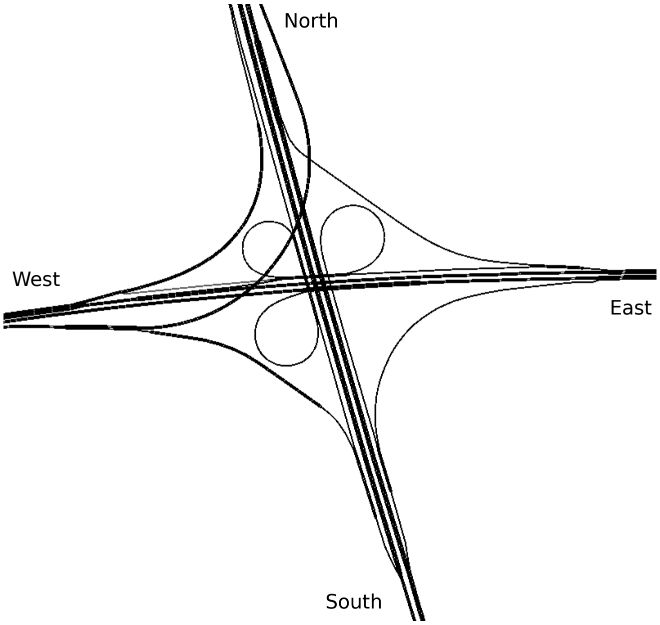


Figure 5. Interchange Münster south, the car with the emergency tries to travel from south direction to west direction and breaks down in the clover interchange line.

scenario. To get two different but still realistic scenarios from the traffic statistic, the crossing traffic from eastern/western directions was left out in the straight scenario. Hence, only traffic from northern and southern directions was present in the straight scenario. In the interchange scenario vehicles started from each direction. In each scenario, 20% of cars were presumed to change from one highway to the other highway with 10% in each direction of the highway. The road traffic was implemented with the traffic flow functionality of SUMO, which regularly introduces vehicles based on the number of vehicles per hour. The scenario consists of a car that drives on the highway in northern direction and wants to change the highway in western direction on the interchange. It breaks down on the clover interchange lane and sends an emergency message. The car drove in north-west direction and hence it has a regular slot in the first half of the frame structure. In each scenario, the emergency was set to three different slots. To slot 1, directly after an emergency slot, to slot 25, in the middle between two emergency slots, and to slot 49, right before an emergency slot. Each configuration was run with 50 repetitions to achieve a good confidence interval.

In addition to the aforementioned scenarios, we conducted a scenario "dense traffic" with additional cars to simulate extremely dense traffic as it would be expected in urban traffic. We conducted it with the same parameters as the "Interchange" scenario, but increased the numbers of vehicles to $13\,600$ vehicles per hour.

V. RESULTS

In this section, we present the results of two different evaluations of the protocol. First, we discuss the results obtained from using two emergency slots and then we show the results with four emergency slots.

A. Results with two emergency slots

For the evaluation of EEVeMAC protocol, we measured two values. The latency from the moment the emergency occurred to the moment the one-hop neighbors receiving the emergency message. The second evaluation value consists of the occurrence of collisions, which were calculated to the arithmetic average per node. The results showed an overall improvement of the latency as further explained below.

1) Latency in straight scenario:
In the straight scenario, there were 21 nodes in transmitting range of the emergency vehicle at the moment of the emergency situation. The emergency message took a median time of $69.99\,\mathrm{ms}$ to reach the one-hop neighbors of the emergency vehicle in the original VeMAC. With EEVeMAC, with the addition of emergency slots, this value was reduced to $16.57\,\mathrm{ms}$ as shown in Figure 6. If the emergency occurred in the first slot after an emergency slot, the median latency was closest to the original protocol with $34.58\,\mathrm{ms}$ (VeMAC) vs. $25.01\,\mathrm{ms}$ (EEVeMAC) as depicted in Figure 7 (a), since there is a good chance that the regular slot of the emergency vehicle is between the slot in which the emergency occurs and the next emergency slot.

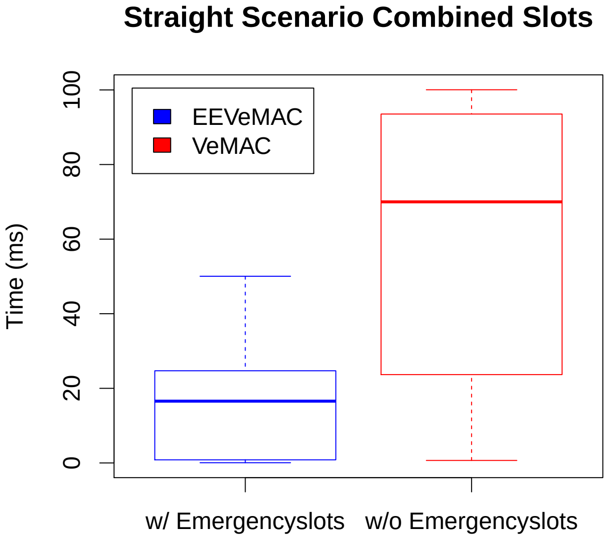
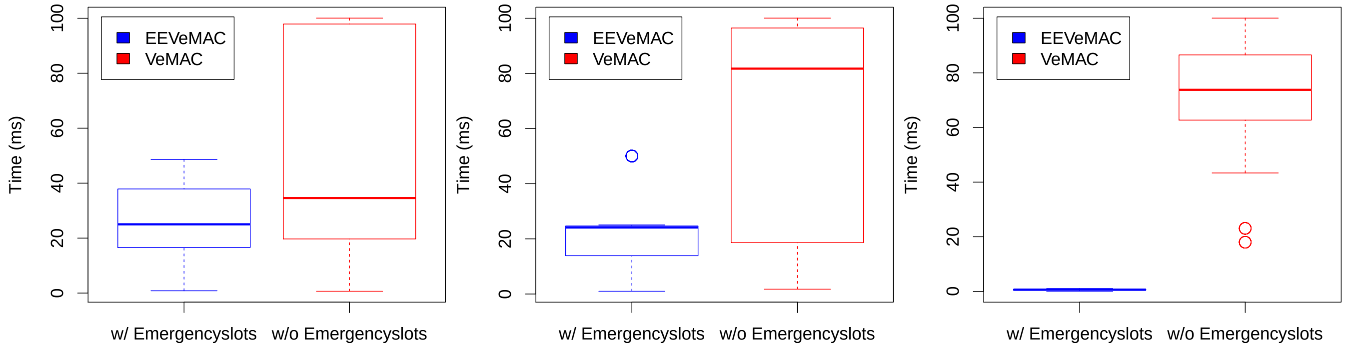


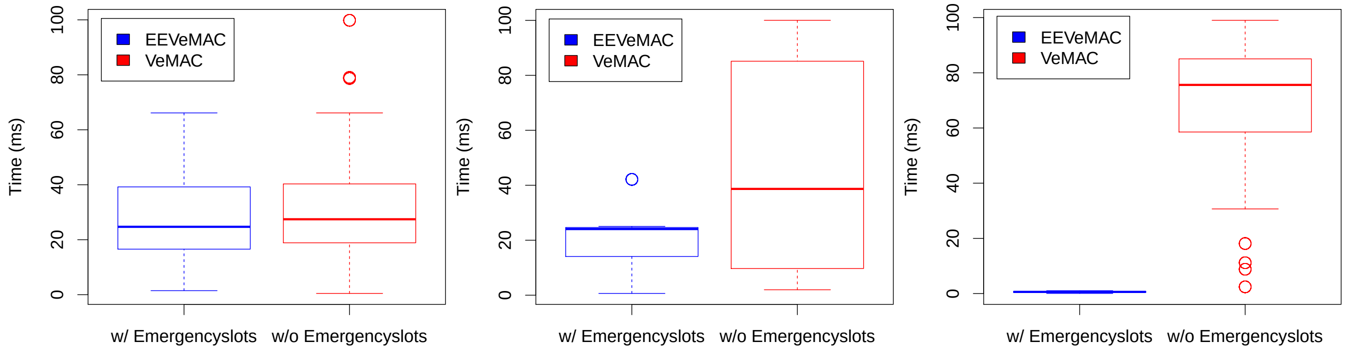
Figure 6. Evaluation results of straight scenario: On the left the latency results of EEVeMAC with emergency slots (w/Emergencyslots), on the right the latency results of original VeMAC without emergency slots (w/oEmergencyslots).

If there is a regular slot in between the emergency and an emergency slot, there is no difference between both protocols as they would both transmit the emergency message in the regular slot. The improvement occurs in the cases where the emergency slot is used. The biggest improvement could be measured with the emergency in slot 49, directly in front of an emergency slot with $73.79\,\mathrm{ms}$ (VeMAC) vs. $0.61\,\mathrm{ms}$ (EEVeMAC) as shown in Figure 7 (c). Without the emergency slots, the emergency vehicle has to wait at least $50\,\mathrm{ms}$ if it does not have slot 49 as its regular slot. It can not transmit in the slot numbers 50-99 since the emergency vehicle is driving in north western direction and hence prefers a slot in the L-set in slot numbers 0-49 of the frame. With the emergency right between two emergency slots, the median latency was improved by $57.61\,\mathrm{ms}$ from $81.73\,\mathrm{ms}$ in the original VeMAC to $24.12\,\mathrm{ms}$ in EEVeMAC with emergency slots as depicted in Figure 7 (b).

2) Latency in interchange scenario: The results of the interchange scenario with traffic flow from each direction showed similar improvements as shown in Figure 8. In this scenario, 35 nodes were present in transmitting range during the emergency situation. The median latency was



(a) Straight scenario - Emergency in slot 1 (b) Straight scenario - Emergency in slot 25 (c) Straight scenario - Emergency in slot 49



(d) Interchange scenario - Emergency in slot 1 (e) Interchange scenario - Emergency in slot 25 (f) Interchange scenario - Emergency in slot 49

Figure 7. Overview of evaluation of latency results for the straight and the interchange scenarios with the emergency in slots 1, 25, and 49. The small red circles in the figures indicate outliers.

improved by factor 3 from 48.73 ms (VeMAC) to 14.66 ms (EEVeMAC). The biggest improvement could be once again measured if the emergency occurred in the slot right before an emergency slot 75.61 ms in the original VeMAC vs. 0.61 ms in the EEVeMAC as depicted in Figure 7 (f), the smallest improvement with the emergency right behind an emergency slot 27.45 ms vs. 24.7 ms (Figure 7 (d)). When the emergency occurred in the middle between two emergency slots, the median latency still shows an improvement of 14.6 ms with 38.67 ms measured in the VeMAC and 24.07 ms in the EEVeMAC as shown in Figure 7 (e).

3) Latency in dense traffic scenario:

In the interchange scenario with additional traffic, 63 nodes were present in range of the emergency vehicle. The results showed overall similar results as in the normal interchange scenario. The median latency was measured slightly higher with 16.05 ms (EEVeMAC) vs. 75.65 ms (VeMAC) as shown in Figure 9.

In the straight scenario with dense traffic configuration the latencies are closer together with 21.99 ms (EEVeMAC) vs. 52.69 ms as shown in Figure 10. The respective results of both scenarios in dense configurations for the different emergency slot placements can be seen in Figure 11. In this scenario, there were 159 nodes in range of the emergency vehicle. In contrast between these two configurations one can see that the latencies remain quite stable in EEVeMAC with 27.05 ms in the straight dense scenario vs. 24.05 ms in the interchange dense scenario for accident slot number 1, 24.08 ms vs. 22.07 ms for slot number 25, and 0.69 ms vs 0.70 ms for slot number 49. In VeMAC, the data is more heterogeneous since they do not have always the same (emergency-) slots to transmit the data. The exact numbers are 59.65 ms vs. 33.05 ms for accident in slot number 1, 51.15 ms vs 82.77 ms for accident in slot number 25, and 46.29 ms vs 85.05 ms for accident slot number 49.

4) Collisions:

The reservation of two slots for transmission of emergency messages results in a higher expectation of collisions. Instead

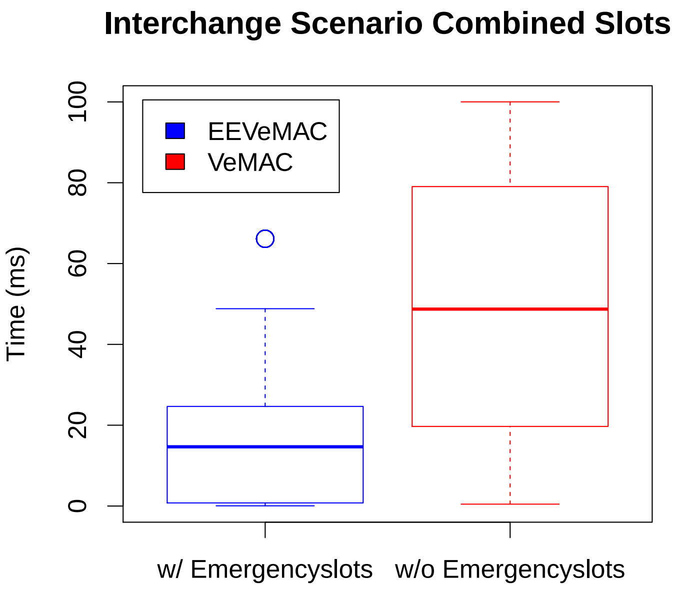


Figure 8. Evaluation results of interchange scenario: On the left the latency results of the EEVeMAC, on the right the latency results of original VeMAC.

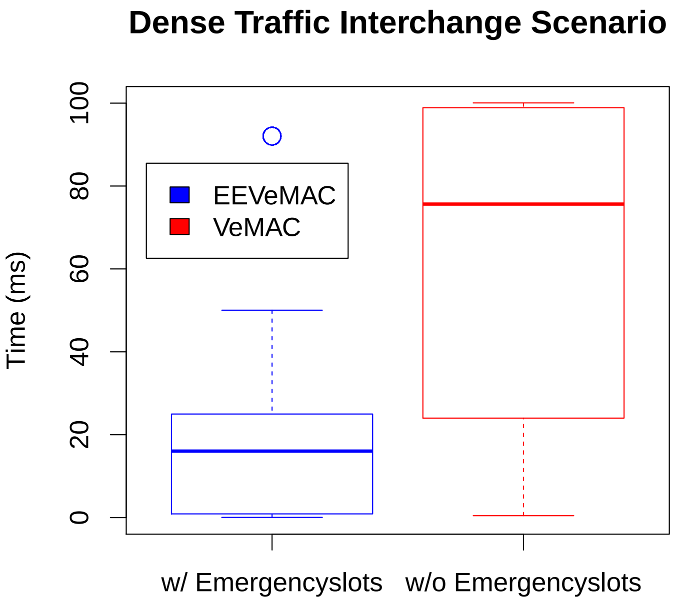


Figure 9. Evaluation results of dense traffic interchange scenario: On the left the latency results of the EEVeMAC, on the right the latency results of original VeMAC. The slots of the three configurations are combined in this diagram.

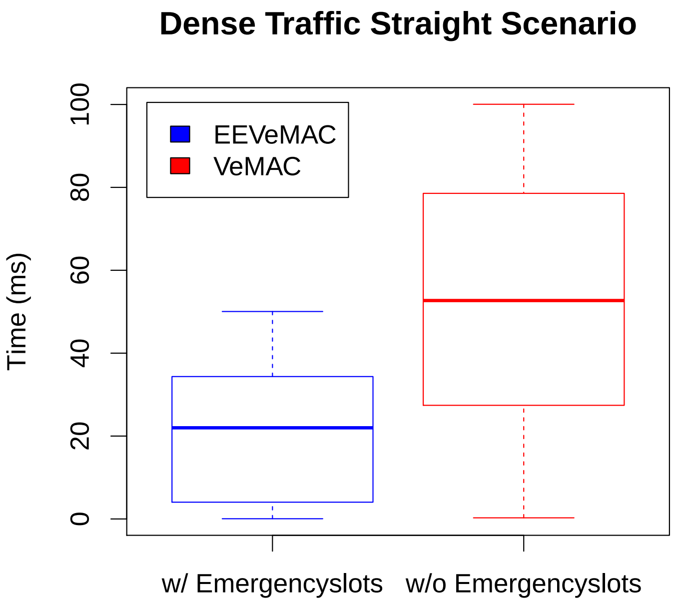


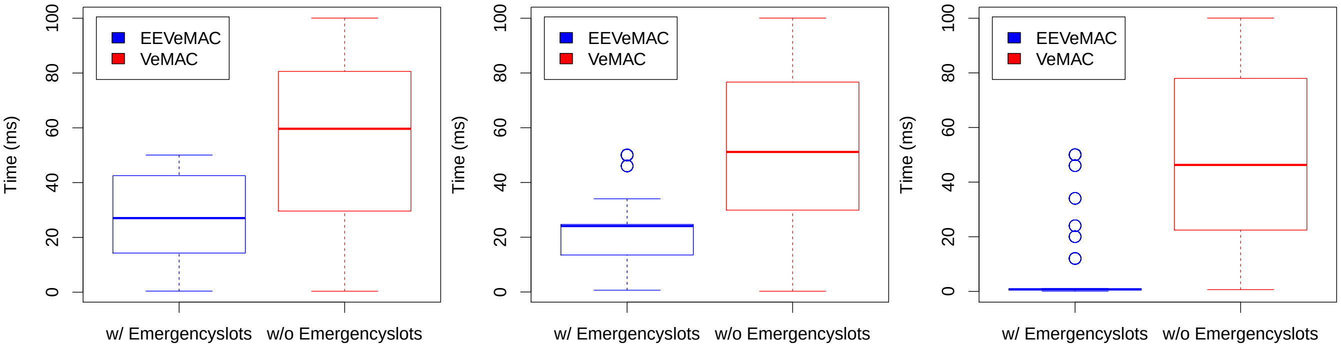
Figure 10. Evaluation results of dense traffic straight scenario: On the left the latency results of the EEVeMAC, on the right the latency results of original VeMAC. The slots of the three configurations are combined in this diagram.

of 100 slots for transmission of their regular message, the nodes only have a maximum of 98 slots to choose from. Therefore, we also measured the number of collisions. As a measurement, we took the average number of collisions per node. The number of collisions increases in the straight scenario from 0.045 average collisions per node in the original VeMAC to 0.047 average collisions per node in the EEVeMAC. The results of the second scenario show that the effect is negligible compared to the effect the number of nodes have. The VeMAC had 0.294 collisions per node whereas the EEVeMAC had 0.290 collisions per node on average. EEVeMAC having lower collisions per node shows that the randomization has a bigger impact on the collisions than the protocol changes in this traffic density. The average number of collisions increases further with additional traffic in the dense traffic scenario. In the simulation runs with VeMAC, 0.528 collisions occurred whereas EEVeMAC measured 0.663 collisions.

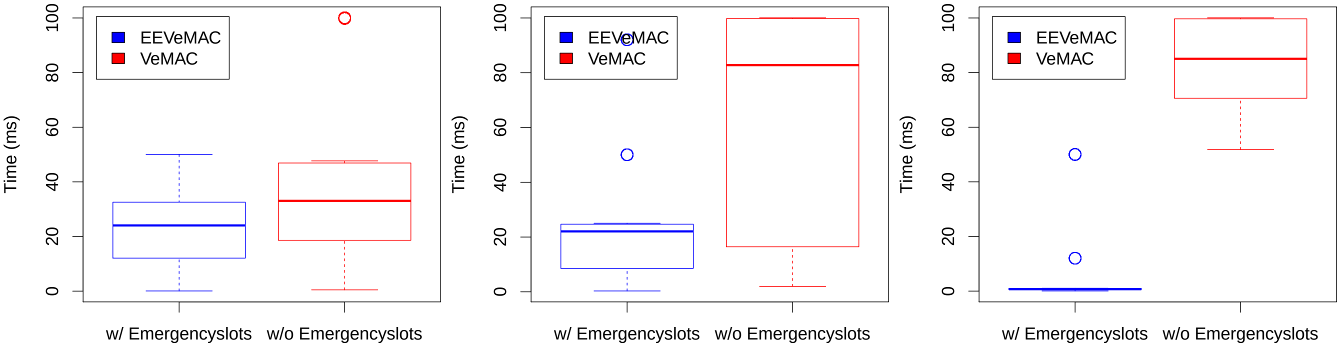
B. Results with four emergency slots

To evaluate the impact of the number of emergency slots on latency, we increased the number of emergency slots to four. These additional slots were added in the middle between the existing emergency slots on slot number 25 and 75. Each simulation configuration was run with the same simulation parameters as before, i.e., emergency occurrence in slot 1, slot 25, and slot 49. The result diagrams are shown in Figure 12.

1) Latency in straight scenario: In the straight scenario with the emergency in slot 1, the median latencies of the configurations with emergency slots were quite close together at 23.14 ms (2 Slots) and 22.81 ms for EEVeMAC (4 Slots). The simulation for VeMAC without emergency slots had a much longer median latency at



(a) Straight scenario-Emergency in slot 1 (b) Straight scenario-Emergency in slot 25 (c) Straight scenario-Emergency in slot 49



(d) Interchange scenario-Emergency in slot 1 (e) Interchange scenario-Emergency in slot 25 (f) Interchange scenario-Emergency in slot 49

Figure 11. Overview of evaluation of latency results for the straight and the interchange scenarios in dense traffic configurations with the emergency in slots 1, 25, and 49. The small red circles in the figures indicate outliers.

58.15 ms as shown in Figure 12 (a). There were several outliers in the variant with only 2 emergency slots as the next possible transmission slot is further away when cars miss the first emergency slots due to collisions or other reasons.

A similar result can be seen in the next scenario Figure 12 (b), with the emergency happening in slot 25, with the median latency of 22.30 ms (2 Slots) and 21.22 ms (4 Slots) for EEVeMAC and 60.09 ms for VeMAC respectively.

The configuration in Figure 12 (c) showed no big difference between both EEVeMAC variants with median latencies around 1 ms (1.00 ms vs. 0.99 ms) as the emergency is right before an emergency slot in both configurations. The VeMAC took longer with a median latency of 58.54 ms.

Additionally, we also run some simulations with the dense straight traffic scenario to examine how the traffic density affects the latency in this case. The results were pretty similar with 21.99 ms combined median latency with two Emergency Slots vs. 20.14 ms combined median latency with four Emergency Slots. The combined results are shown Figure 13.

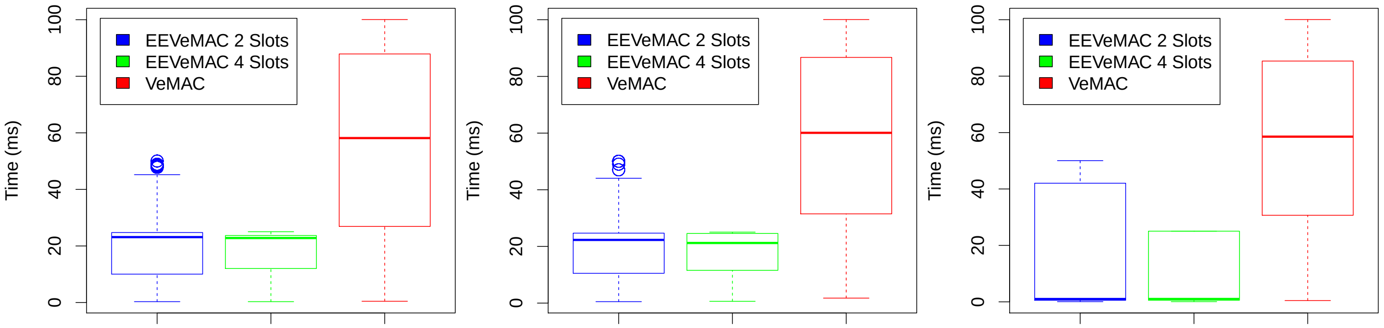
2) Latency in interchange scenario:

The simulation configuration in Figure 12 (d) with four emergency slots showed a reduction of the latency for the EEVeMAC. The median latency of four slots EEVeMAC was measured to be 23.13 ms and as much as expected lower than 25 ms maximum needed to the next emergency slot. This also shows in the absence of latency measurements higher than 25 ms. With only two emergency slots, this median rises to 26.75 ms, but in case of VeMAC without emergency slots, it is the highest at 38.80 ms.

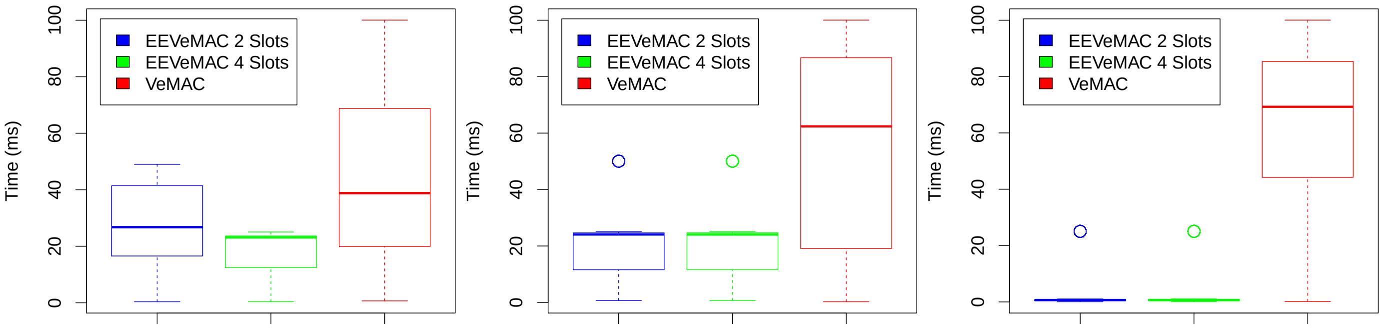
In both of the next two simulation configurations in Figure 12 (e) and Figure 12 (f), the results of the two slots EEVeMAC and the four slots EEVeMAC were the same as they had the same configurations of emergency slots from their respective position onwards, whereas the VeMAC has higher latency as expected.

3) Collisions:

In the straight scenario, the mean number of collisions was measured lower in the four slots scenario than in the two slots scenario. Since the results are very close together with 0.0098 collisions per node in the two slots scenario in comparison to



(a) Straight scenario - Emergency in slot 1 (b) Straight scenario - Emergency in slot 25 (c) Straight scenario - Emergency in slot 49



(d) Interchange scenario - Emergency in slot 1 (e) Interchange scenario - Emergency in slot 25 (f) Interchange scenario - Emergency in slot 49

Figure 12. Overview of evaluation of latency results for the straight and the interchange scenarios with the emergency in slots 1, 25, and 49. The small red circles in the figures indicate outliers.

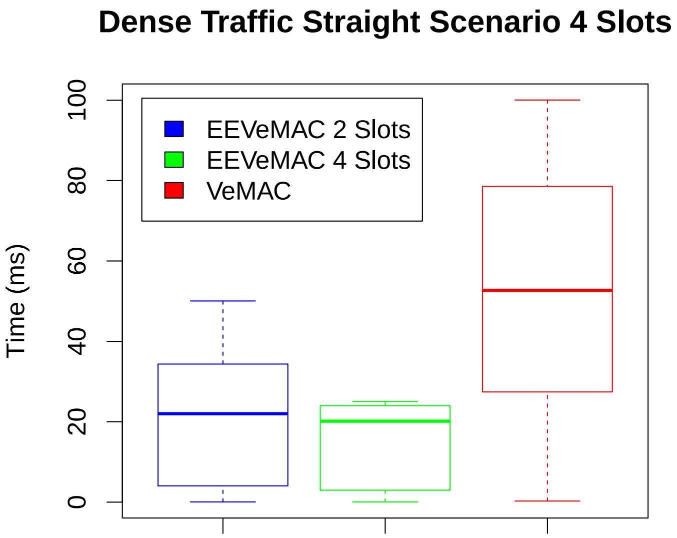


Figure 13. Evaluation results of dense straight traffic scenario: On the left the latency results of the EEVeMAC with two Emergency slots, in the middle the results of the EEVeMAC with four Emergency slots, on the right the latency results of original VeMAC. The slots of the three configurations are combined in this diagram.

0.0092 collisions per node in the four slots scenario.

It is assumed that it is an outcome from the randomness and does not have the cause in the changed slot configuration. Although the configuration with no emergency slots showed fewer mean collisions per node with 0.0068. The traffic flow had a much bigger impact on the collision rate in the interchange scenario.

The mean number of collisions increased by two magnitude up to 0.681 collisions per node in the two slot scenario and 0.685 collisions with four slots scenario. Without emergency slots, it had still a similar magnitude with 0.615 average collisions per node.

VI. CONCLUSION

The introduction of emergency slots in VeMAC shows great improvements for the transmission of high-priority emergency messages. Instead of median latencies of up to 80+ ms we achieved in our simulation experiments a maximum of median latencies smaller than 25 ms. The latencies were reduced by factor of 3-4. The median and average latencies were improved in each study configuration. The reduction of available slots for regular transmission through the reservation of emergency slots had negligible effects on the rate of collisions. In situations where several vehicles try to send out an emergency message at the same time, competition emerges and latency increases as the vehicles fail to acquire the emergency slot. The vehicles can still use their normal slots to transmit the emergency message, which means that the average latency converges to the maximum latency of VeMAC, e.g., $100\,\mathrm{ms}$.

Further, with the introduction of four emergency slots, median latencies were almost consistent with the two emergency slots configurations. Overall, EEVeMAC with emergency slots shows great improvements for transmission of time-critical traffic compared to VeMAC.

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