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Analysis of Cooperative Awareness Message Rates in VANETs

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***Abstract*—To support applications for environment perception in Vehicular Ad-Hoc Networks (VANETs), vehicles send Cooperative Awareness Messages (CAMs) via wireless broadcast to inform other vehicles about their status. Each message received by a vehicle is processed by several application modules that run on hardware with limited resources whose capacity is not yet defined. Therefore, the received rate of CAMs is a crucial input for the development of series VANET products. In this paper, we quantify the received rate of CAMs and show that it can be high even for a low fraction of vehicles generating CAMs. We simulate road traffic in typical highway scenarios and estimate sent CAM rates. We introduce the notion of relative channel load and present a new approximative channel model to determine a vehicle's message reception probability. We use that model to simulate a vehicle's received CAM rates and propose a simple approximation formula.**

I. INTRODUCTION

Communication between road side infrastructure and vehicles has been identified as a key technology to further increase traffic safety, improve the driving comfort, and raise ecological and economic efficiency [1]. These approaches are usually called *Vehicular Ad-Hoc Networks* (VANETs), *Car-to-Car-Communication* (Car2Car, C2C), or *Vehicle-to-Vehicle Communication* (V2V).

In the last years the standardization of protocols and technologies has evolved to a phase of harmonization among continents and validation through extended field tests [2]. In Europe two types of messages are defined for information exchange among participating vehicles: event-based messages and status information messages [3][4]. Frequently updated status information messages called *Cooperative Awareness Messages (CAMs)* are used by their receivers to create and maintain an internal environmental map. From this database they can extract information about the traffic situation by analyzing vehicle trajectories and recognizing traffic patterns.

In contemporary field operational tests and experiments, the processing of CAMs is not a challenge, but that will change in the future for several reasons. First, test vehicles usually have powerful hardware installed. Facing the introduction of VANET technology in series vehicles, this will change due to their resource-constraint hardware and architecture. Second, the very few participants in field operational test do not generate a CAM rate that is representative for the future. The CAM load will increase with the penetration rate of VANET technology in series vehicles. Assuming its start in 2015, as stated in a memorandum of understanding among European car manufacturers, and considering the average lifetime of a car of about 8.5 years, it is obvious that also the early adopters' cars have to be able to cope with rising penetration rates [5][6][7]. This motivates our analysis of future CAM rates.

Our methodology is as follows. We first simulate traffic on two typical highway scenarios. Based on the vehicles' traces we derive the sending instants of CAMs. We introduce the notion of a relative channel load and a new statistical channel model to compute the probability for correct reception of a sent CAM depending on the distance from the sender and the relative channel load. This allows to statistically determine the rate of CAMs received by VANET-equipped vehicles. We also propose two approximation formulas to calculate the relative channel load and the number of CAMs received by a vehicle. We show that the obtained results match the simulated data quite closely. We use the approximation for a parameter-study of the relative channel load and for validation purposes.

The remainder of this paper is organized as follows. Section II briefly reviews related work. In Section III we introduce the standardized message types and their triggering conditions. Section IV presents the simulation setup and scenarios used to evaluate the rate of sent CAMs. In Section V we introduce a new statistical channel model for the message transmission probability. In Section VI we investigate the channel load by extending our simulation and using an estimating formula, which we use in Section VII to determine the rates of received CAMs. Finally, Section VIII summarizes this work and provides an outlook on further research.

II. RELATED WORK

While standards for VANET technologies are currently finalized, field operational tests are conducted to investigate their interoperability and feasibility. In Europe there are three big field operational tests in this context: sim^{TD} (Germany), score@F (France) and DRIVE C2X (international) [8][9][10]. All of these tests utilize powerful hardware which will not be used for series vehicles because of robustness, size and cost.

There are some projects like VEINS and VSimRTI which provide a complete tool chain for VANET simulations

[11][12]. We chose to build our own tool chain to make use of our own channel model and the controllability of all simulation modules.

Torrent-Moreno et al. conducted an analysis of the transmission rates in a VANET simulation [13] for an arbitrary scenario. However, their work was published before most of the standards regarding VANETs where settled. For example they assume fixed message sending rates of 10 Hz.

In several papers investigations on the radio transmission quality in real experiments have been conducted (e.g. [14][15]). In general, line-of-sight is the key for good message transmission probability. Because of this we focused on scenarios where line-of-sight between communicating vehicles can be assumed.

A statistical channel model for the VANET message reception probability was proposed and developed in [16][17] based on studies in [18]. We adapt this channel model by incorporating a simple representation for the hidden station effect. This effect was identified to be the dominant one for multiple sender scenarios in a non-congested channel [19].

III. VANET MESSAGE TYPES AND MESSAGE TRIGGERS

The European Telecommunications Standards Institute (ETSI) defined two message types to support VANET applications: Decentralized Environmental Notification Messages (DENMs) and Cooperative Awareness Messages (CAMs). We briefly review their use and describe under which conditions they are triggered.

A. Decentralized Environmental Notification Message

In VANETs, vehicles notify other traffic participants about specific events on or near the roads. This notification is carried by a DENM. Each DENM is the result of an event detection process conducted by the message sender and, therefore, a DENM occurs infrequently [3]. Because of their rare occurrence, DENMs do not create a large processing load at the receiver so that we can neglect them in a load analysis.

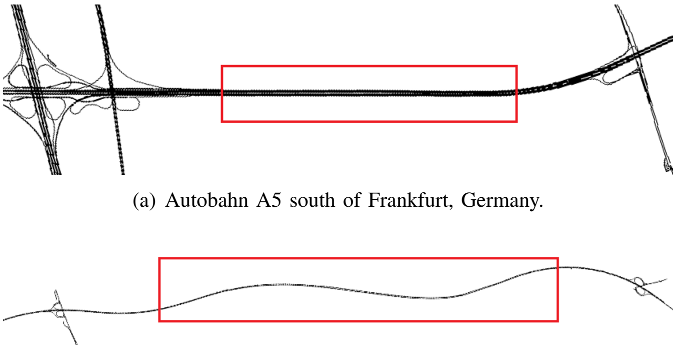
B. Cooperative Awareness Messages

All vehicles in a VANET should be able to track their surrounding traffic situation. To facilitate this, every vehicle (and certain road side stations) sends out status messages on a regular basis. The status messages contain information like message identifier, station type, position, heading, speed, acceleration, curvature and more. Upon reception and interpretation of these status messages the receiver can create a so-called local dynamic map (LDM). This status information is conveyed by a CAM [4].

The more status messages are disseminated among traffic participants, the more precisely and up-to-date each of them can perceive the environment. To avoid wireless channel congestion and unnecessary status updates the CAM sending mechanism is triggered only when a set of rules is met:

- The current heading of the vehicle differs at least 4 ° from the heading in the last CAM **or**
- the current position of the vehicle differs at least 4 m from the position in the last CAM **or**
- the current speed of the vehicle differs at least $0.5\,\frac{\mathrm{m}}{\mathrm{s}}$ from the speed in the last CAM **or**
- the last CAM was sent 1 s earlier.

These conditions have to be checked every T_{Off} [20][3]. Usually T_{Off} is set to 100 ms. To avoid channel congestion, T_{Off} is set to higher values if the channel load exceeds 25 %.


(a) Autobahn A5 south of Frankfurt, Germany.

(b) Autobahn A6 west of Nuremberg, Germany.

Fig. 1. Simulated road sections. The boxed areas are used for the statistics.

IV. ESTIMATION OF SENT CAM RATES

In this section we describe the methodology for road traffic simulation and present two realistic road traffic scenarios. Based on the vehicles' movement traces, the instants for CAM generation are computed which allows the estimation of CAM send rates. Numerical results are discussed.

A. Road Traffic Simulation

We chose the microscopic and continuous traffic simulator SUMO for the vehicle trace generation [21]. This simulator is well-known in the field of VANET simulations and provides efficient calculations even in big scenarios [22][23].

B. Derivation of CAM Generation Instants

Based on a vehicle trajectory dump created with SUMO we execute the CAM triggering algorithm as described in III-B. As long as a vehicle has not left the simulated map section, for each simulation time step a check is performed whether the conditions for the generation of a new CAM are met. If so, the CAM and its generation time are logged and collected for statistics.

C. Road Traffic Simulation Scenarios

The chosen traffic scenarios are based on two map sections of the Autobahn A5 south of Frankfurt and of the Autobahn A6 near Nuremberg in Germany (see Figures 1(a) and 1(b)). The first road segment has eight lanes in parallel while the second road segment has four parallel lanes. In both road segments there are no walls and only a few small objects between the lanes. Assuming the antennas to be mounted on top of the vehicles a line-of-sight can almost always be guaranteed. Hence, good radio transmission quality is available between both driving directions.

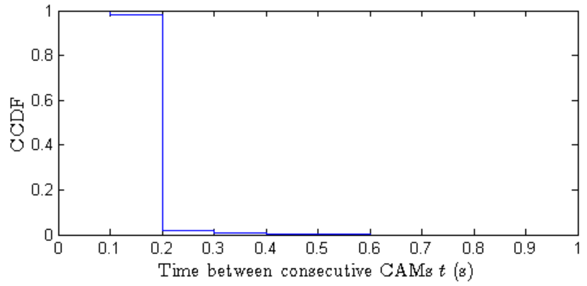


Fig. 2. Complementary cumulative distribution function of the time $T^{\text{CAM}}_{\text{sent}}$ between consecutive CAMs ($P\left(T^{\text{CAM}}_{\text{sent}} > t\right)$).

We designed the vehicle depart settings and sources in a way that typical high traffic density at moving traffic is prevailing. Also we used the road topology with highway interchanges and ramps to create typical road traffic entropy to avoid homogeneous and unnatural effects.

The map data is extracted from the OpenStreetMap project using the jOSM tool [24].

Our simulation scenarios cover about 8000 (A5) and 6000 (A6) vehicles in a time frame of one hour with time steps of 100 ms.

D. Numerical Results

Figure 2 shows the complementary cumulative distribution function (CCDF) of the time $T^{\text{CAM}}_{\text{sent}}$ between two consecutive CAMs that are triggered by a single vehicle. We identify the time between most consecutive CAMs is 200 ms. This is clearly related to the movement pattern of the vehicles in our simulation and the fact that the trigger conditions are checked only every 100 ms. All vehicles with a speed between $72\,\frac{\text{km}}{\text{h}}$ and $144\,\frac{\text{km}}{\text{h}}$ send a CAM every 200 ms because they have changed their position by more than 4 m within that time. These are typical cruise speeds in free or synchronized traffic on highways [25]. Speeds faster than $144\,\frac{\text{km}}{\text{h}}$ induce higher CAM rates but also lead to a lower vehicle density since larger safety distances are required.

V. A New Channel Approximation Model

We develop a new statistical model for the radio channel that essentially computes the reception probability of a message as a function of the channel load and the distance from the sender. In the remainder of this paper, we use this function to simulate the reception of a sent CAM by other vehicles. This is far simpler than an accurate discrete-event-based network simulator like ns-2 or OMNet++ and still captures the most relevant characteristics of the radio channel with sufficient accuracy for our purposes.

We first define the relative channel load. The new combined channel model covers two aspects: signal attenuation in the presence of a single sender-receiver pair and the hidden station phenomenon which is the dominating effect in the presence of multiple senders and low channel loads [19].

A. Definition of Relative Channel Load

A vehicle's antenna obtains signals from all senders within its communication range with radius $d^{\text{comm}}_{\text{range}}$. The rate of messages from these sources is $r^{\text{cr}}_{\text{sent}}$. The fraction of $r^{\text{cr}}_{\text{sent}}$ and the default transmission bandwidth of 802.11p, which is $6\,\frac{\text{Mbit}}{\text{s}}$, define the relative channel load

$$\rho = r^{\text{cr}}_{\text{sent}} \cdot \frac{200\,\text{byte}}{6\,\frac{\text{Mbit}}{\text{s}}} \tag{1}$$

for a message size of 200 bytes [4][26][19].

B. Signal Attenuation for a Single Sender and Receiver

The Nakagami m-distribution is known to enable an accurate characterization of signal attenuation in wireless channels, which was validated by experimental results for typical VANET setups [27][18]. Killat et al. proposed to use a tuned model of the Nakagami m-distribution providing the reception probability of a message depending on the distance d between sender and receiver. They validated their model with a discrete-event network simulation [16][17].

The model performs a case analysis because it considers the Friis path loss model to the two-ray ground model at crossover distance [28][29]

$$d_{co} = 4 \cdot \pi \frac{h_s \cdot h_r}{\lambda}, \tag{2}$$

where h_s and h_r are the installation heights of the sender's and receiver's antennas and λ is the wavelength of the signal. For distances greater than d_{co} the signal reflection on the ground as formulated by the two-ray ground model needs to be respected. Killat et al. derived the following formula for the transmission success rate

$$P^{\text{success}}_{\text{Nakagami}}(d) =$$
$$\begin{cases} e^{-3\left(\frac{d}{d^{\text{comm}}_{\text{range}}}\right)^2} \cdot \left(1+2\left(\frac{d}{d^{\text{comm}}_{\text{range}}}\right)^2+\frac{9}{2}\left(\frac{d}{d^{\text{comm}}_{\text{range}}}\right)^4\right), \text{if } d \leq d_{co} \\ e^{-3\gamma\left(\frac{d^2}{d^{\text{comm}}_{\text{range}}}\right)^2} \cdot \left(1+2\gamma\left(\frac{d^2}{d^{\text{comm}}_{\text{range}}}\right)^2+\frac{9}{2}\gamma^2\left(\frac{d^2}{d^{\text{comm}}_{\text{range}}}\right)^4\right), \text{if } d > d_{co}. \end{cases}$$

The parameter $d^{\text{comm}}_{\text{range}}$ is the maximum achievable communication range. The parameter γ depends on the height of both sender and receiver antennas and the wavelength of the signal, and can be calculated as

$$\gamma = \left(\frac{\lambda}{4 \cdot \pi \cdot h_s \cdot h_r}\right)^2 = (d_{co})^{-2}. \tag{3}$$

C. Hidden Station Phenomenon for Multiple Senders

In multiple sender scenarios, the message reception probability is lower than in single sender-receiver scenarios. The dominating phenomenon in multiple sender scenarios is the hidden station effect [19]. It is caused by several sending nodes in reach of a receiving node but with each sending node being out of the reach of the other sending nodes. Therefore, the sending nodes are not able to coordinate the channel access and possibly send messages at the same time. This leads to colliding signals at the receiving node and hence decreases the probability for correct reception.

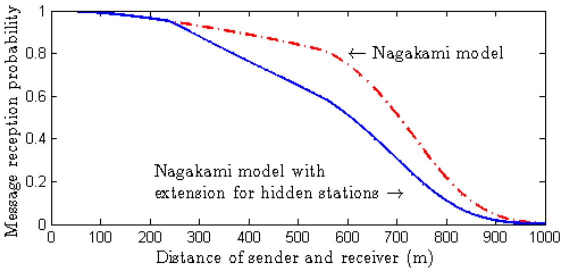


Fig. 3. Message reception probability for channel load $\rho = 0.2$.

The hidden station effect has different manifestations, but the dominant one comes into place after the hidden station range d_{HS} which is a section of the overall communication range $d_{\text{range}}^{\text{comm}}$. With a required SNR threshold $\Gamma_{d_{\text{HS}}}$ for successful decoding and a path loss coefficient μ, d_{HS} can be computed as

$$d_{\text{HS}} = \frac{d_{\text{range}}^{\text{comm}}}{1 + (\Gamma_{d_{\text{HS}}})^{\frac{1}{\mu}}}. \tag{4}$$

For constant μ, $P_{\text{hidden}}^{\text{loss}}$ increases linearly with increasing distance [19]:

$$P_{\text{hidden}}^{\text{loss}}(d, \rho) \approx 1.5 \cdot \rho \cdot \frac{T_{\text{air}}}{T_{\text{air}} + T_{\text{CA}}} \cdot \frac{d - d_{\text{HS}}}{d_{\text{HS}} - 1\,\text{m}}, \tag{5}$$

where T_{air} corresponds to the air time of a packet and T_{CA} corresponds to the channel access time.

D. Combination of Effects

We combine $P_{\text{Nakagami}}^{\text{success}}$ and $P_{\text{hidden}}^{\text{loss}}$ as independent effects and calculate the message reception probability

$$P_{\text{combined}}^{\text{success}}(d, \rho) = (1 - P_{\text{hidden}}^{\text{loss}}(d, \rho)) \cdot P_{\text{Nakagami}}^{\text{success}}(d). \tag{6}$$

Figure 3 illustrates the output of $P_{\text{combined}}^{\text{success}}$ for the chosen set of channel parameters[1].

VI. ESTIMATION OF RELATIVE CHANNEL LOADS

We first explain how the CAM rates are derived from the logged CAMs of the road traffic simulation in Section IV. Then, we propose a simple formula that approximates that rate without a detailed road traffic simulation. We show that the formula matches the simulated CAM rates quite well and use it to illustrate the dependence of the CAM rates on various parameters.

A. Simulation of Relative Channel Loads

In Section IV we used the output of the road traffic simulation to determine the CAM sending instances of vehicles. We now use these data in addition to the information whether a vehicle is equipped with VANET technology to determine the rate r_{sent}^{cr} of sent CAM messages in the vicinity of a receiver. Depending on the penetration rate φ, we first determine which vehicles actually send CAMs. Then we summarize the number of broadcasted CAMs within a range of $d_{\text{range}}^{\text{comm}}$ and calculate the time-dependent rate of sent CAMs r_{sent}^{cr} for each receiver. Using r_{sent}^{cr} and Equation (1) we can calculate the perceived relative load ρ for each receiver at any simulation step. The mean relative channel load $\overline{\rho}$ is calculated as the average of relative channel loads over all simulated intervals and all receivers. We use it for validation and illustration purposes.

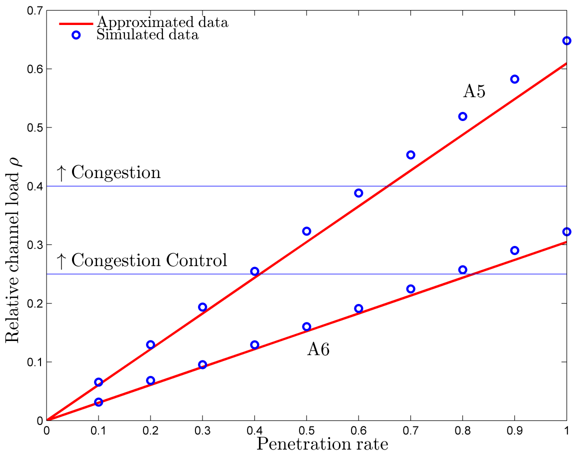


Fig. 4. Simulated and approximated relative channel loads ($l_{\text{A5}} = 8, l_{\text{A6}} = 4, \sigma = \frac{1}{35\,\text{m}}, \overline{T}_{\text{sent}}^{\text{CAM}} = 0.2\,\text{s}$).

B. Approximation of Relative Channel Loads

We approximate the average relative channel load with Equation (1) and calculate the average rate of messages in the vicinity of each receiver by

$$\overline{r}_{\text{rcvd}}^{\text{cr}} = 2 \cdot l \cdot d_{\text{range}}^{\text{comm}} \cdot \sigma \cdot \varphi \cdot \frac{1}{\overline{T}_{\text{sent}}^{\text{CAM}}}, \tag{7}$$

where l is the number of parallel driving lanes, multiplied by factor 2 for both directions ahead and behind the receiver, communication range $d_{\text{range}}^{\text{comm}}$, σ is the vehicle density on a single lane, expressed in vehicles per meter, φ is the penetration rate, and $\overline{T}_{\text{sent}}^{\text{CAM}}$ is the average time between consecutive CAMs sent by a single vehicle. The underlying assumptions are straight roads, equidistantly placed vehicles, and constant vehicle speeds leading to constant time $\overline{T}_{\text{sent}}^{\text{CAM}}$ between two consecutive CAMs from a single vehicle.. Additional numerical assumptions are the penetration rate φ, and the vehicle density σ.

C. Numerical Results

The circles in Figure 4 show the average relative load $\overline{\rho}$ computed for the two considered simulation scenarios. The values depend about linearly on the penetration rate φ.

In European standardization multiple layers implement congestion control, including the access layer [30]. These congestion control mechanisms take effect at about 25 % channel load. This load threshold is reached in the A5 scenario for a penetration rate of 40 % and in the A6 scenario for a penetration rate of 80 %. The congestion control mechanism mitigates congestion by using several regulators like transmit power control, transmit rate control, transmit data rate control

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[1] $\Gamma_{d_{\text{HS}}} = 10$, $T_{\text{air}} = 0.267\,\text{ms}$, $T_{\text{CA}} = 0.114\,\text{ms}$, $\mu = 2$, h_s, $h_r = 1.5\,\text{m}$, $d_{\text{range}}^{\text{comm}} = 1000\,\text{m}$, $\lambda = 0.0508\,\text{m}$.

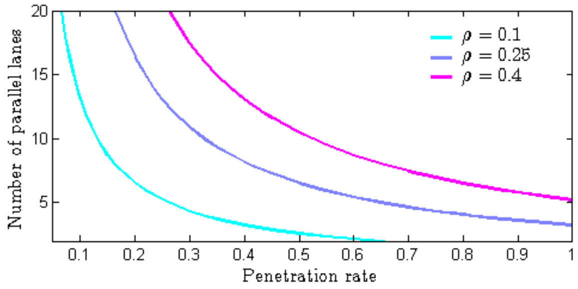

Fig. 5. Channel load ρ as a function of penetration rate φ and number of lanes l.

and transmit access control. This effectively means that the transmission rate of a sender is reduced which leads in this scenario to message queuing, delay, and loss. Thus, CAM information may be outdated when arrived at the receiver. To avoid such situations, the time between consecutive CAMs needs to be increased to generate them less frequently, which in turn decreases the surrounding awareness of the receiving vehicles. As we did not integrate congestion control in our simulation and approximation, the relative channel loads are overestimated. From a relative load of $40\,\%$ on, the channel is even considered congested. We conclude that CAMs can fill the radio channel in the presence of moderate and high penetration rates in the future to such an extent that the available transmission capacity might not suffice to deliver all CAMs in time.

The solid line shows the corresponding results approximated by Equation (7). We used $\overline{T}_{\text{sent}}^{\text{CAM}} = 0.2\,\text{s}$ according to our results from Section IV-D and $\sigma = \frac{1}{35\,\text{m}}$ based on our experience. We observe that simulated and approximated results are in good accordance. On the one hand, this validates the simulation results, on the other hand, this suggests to use the approximation formula for parameter studies. Their results are compiled in Figure 5. The three lines show for which penetration rate and for how many lanes a relative channel load of $10\,\%$, $25\,\%$, and $40\,\%$ is achieved. For large highways, congestion control will be needed already for penetration rates lower than $40\,\%$[2].

VII. ESTIMATION OF RECEIVED CAM RATES

We use the presented channel model to estimate the received CAM rates of receivers based on the calculated channel load and the logged CAMs. We basically determine which CAM within the communication range $d_{\text{range}}^{\text{comm}}$ is correctly received by each vehicle. First, we calculate the received CAM rates accurately based on the simulation results from Section IV, then we estimate it with an approximation formula. Finally, we discuss the simulation results and compare them with those from approximation.

A. Simulation of Received CAM Rates

The simulation in Section IV determines all vehicles that send out a CAM in a particular time step of 100 ms. In Section VI we derived for each potential receiver the channel load of CAMs within its communication range. We compute the reception probability by a potential receiver for all logged CAMs depending on the distance to the CAM sender and the channel load, and simulate according to that probability whether the CAM is received. The CAM rate received by a vehicle $r_{\text{rcvd}}^{\text{CAM}}$ is computed by counting all received CAMs within the communication range $d_{\text{range}}^{\text{comm}}$ of the receiver and within a simulation step, and adding up this numbers for $1\,\text{s}$.

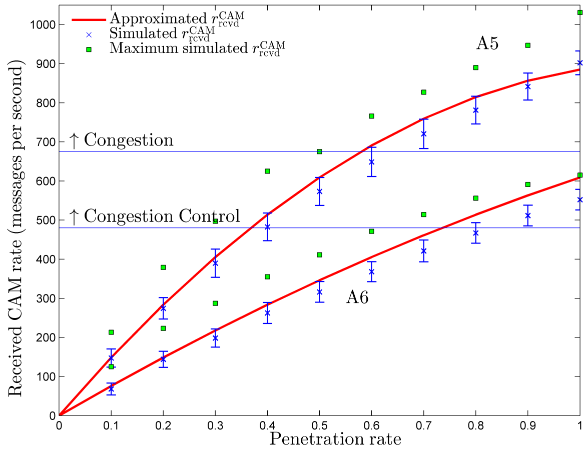

Fig. 6. Comparison of simulation (discrete values: mean, standard deviation and maximum values) and approximative evaluation for the received message rates ($l_{\text{A5}} = 8, l_{\text{A6}} = 4, \sigma = \frac{1}{35\,\text{m}}, \overline{T}_{\text{sent}}^{\text{CAM}} = 0.2\,\text{s}$).

B. Analysis of Received CAM Rates

We assume that the sent CAMs are equally distributed within the communication range of a receiver. The reception probability decreases with increasing distance to the sender. We further assume that the width of the lane is small compared to the communication range $d_{\text{range}}^{\text{comm}}$ and approximate the average reception probability for a CAM by $\frac{\int_0^{d_{\text{range}}^{\text{comm}}} P^{\text{loss}}(d,\rho)\text{d}d}{d_{\text{range}}^{\text{comm}}}$. Multiplication with the CAM rate in the communication range of a receiver yields the received CAM rate

$$n_{\text{rcvd}}^{\text{CAM}} = 2 \cdot l \cdot c \cdot d_{\text{range}}^{\text{comm}} \cdot \sigma \cdot \varphi \cdot \frac{\int_0^{d_{\text{range}}^{\text{comm}}} P^{\text{loss}}(d,\rho)\text{d}d}{d_{\text{range}}^{\text{comm}}}. \qquad (8)$$

as approximation of the received CAM rate.

C. Numerical Results

The discrete values in Figure 6 show the simulated received CAM rates depending on the penetration rate with average values and standard deviations. They increase less than linearly with the penetration rate because an increasing relative channel load reduces the reception probability of CAMs. For CAM rates of up to 500 messages per second, the channel model is sufficiently accurate in the absence of congestion control. That CAM rate easily occurs on the A5 and the A6 for a penetration rate of $40\,\%$ and $80\,\%$, respectively. Moreover, CAM rate peaks exceeding that boundary might appear even with congestion control available because such a mechanism needs some time to take effect. We observe high received

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[2] The Highway 401 in Toronto, Canada, has 20 lanes in parallel, 10 in each direction.

CAM rates even for low penetration rates. In the A5 scenario, we can get up to 200 messages per second for a penetration rate of 10 %.

We deduce that series vehicles equipped with VANET technology according to current standardization have to handle several hundreds of messages per second in certain scenarios. Considering the usual restrictions for automotive hardware and software regarding robustness, size and cost, there are two ways to deal with this challenge, with the option to combine both of them. First, the hardware capabilities can be sized sufficiently, which in turn leads to higher costs. Second, the architecture for the processing of each of the received messages can be designed in an efficient way. Using this approach we are also able to install measures which can cope with critical loads by processing the most important CAMs preferredly. We have proposed such an algorithm in [31].

VIII. Conclusion and Future Work

We analyzed the rates of sent CAMs for two realistic road traffic scenarios. We provided a simplified channel model that is valid in the absence of congestion control effects. We simulated the channel load and provided an approximation formula, and simulated received CAM rates per vehicle and also provided an approximation formula.

Our evaluation shows that sent CAM rates can be large enough to cause congestion on the radio channel so that congestion mechanisms for CAM generation are required, even for moderate penetration rates of VANET technology.

The rate of received CAMs can be easily in the order of 500 messages per second that future series vehicles need to handle. This requires either hardware with sufficient processing power for CAM rates in that order of magnitude or a CAM pre-selection algorithm that effects that only most important CAMs are processed by the hardware.

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