Advanced Carrier Sensing to Resolve Local Channel Congestion

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ABSTRACT

Communication performance in VANETs under high channel load is significantly degraded due to packet collisions and drops, also referred to as local channel congestion. So far, research was focused on the control of transmit power and limitation of the messages rate to mitigate the effects of high load. Few attention has been paid to the carrier sensing setup, i.e controlling *when* the channel is indicated as busy. Previous work identified Clear Channel Assessment (CCA) as part of carrier sensing as an efficient way of controlling spatial reuse under high load. The CCA threshold determines at which received power level the channel is sensed busy. In this paper, we propose a stepwise CCA Threshold Adaptation (CTA) depending on how long a packet has been waiting for medium access. This robust approach mitigates significantly the problem of local message drops and hence local congestion. The simulation study confirms the reduction of the average and maximum medium access delay as well as the prevention of message queue drops. Even under inaccurate CCA thresholds among the vehicles, fairness in medium access can be maintained by using CTA. In all cases, the awareness of each vehicle is dramatically improved within the safety-critical area of each vehicle.

Categories and Subject Descriptors

C.2.1 [**Network Architecture and Design**]: Distributed networks, wireless communication

General Terms

Algorithms, Performance, Reliability, Standardization

Keywords

Vehicular Ad-Hoc Networks, VANET, Carrier Sensing

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1. INTRODUCTION

In Vehicular Ad-Hoc Networks (VANETs), vehicles exchange information with surrounding vehicles by broadcasting event-driven Decentralized Environmental Notification Messages (DENMs) as well as periodic Cooperative Awareness Messages (CAMs). Based on this information, active safety applications are able to detect dangerous situations like a potential collision at an intersection.

Since active safety applications should operate in all traffic situations, even at high vehicle density, the periodic exchange of CAMs has to work properly. This has to be ensured by the communication system, in particular by the medium access control (MAC) protocol.

The de-facto standard for MAC and Phy in VANETs is IEEE 802.11p [9]. It defines a medium access scheme based on Carrier-Sense Multiple Access (CSMA) with Collision Avoidance (CA). Prior to a transmission, each station determines if the channel is clear by measuring the currently received signal strength. Two cases are distinguished: First, if an OFDM signal can be detected, a threshold of -85 dBm is applied. Second, if no OFDM signal can be detected, a threshold of -65 dBm is applied which we will call *CCA threshold* in the remainder of this paper. The CCA threshold is set higher than the first threshold because of different requirements in Wi-Fi appliances as explained in [20]. The CCA threshold is only considered by the carrier sensing if two or more concurrent transmissions overlap. The overlap can results in a low signal-to-noise ratio which makes it impossible to detect an OFDM signal. Thus, controlling the CCA threshold is related to the spatial reuse under high channel load.

Since transmitter-part and receiver-part of a transceiver are in relation to each other, the specification of maximum transmit power and minimum receiver sensitivity correlate with each other so that estimations of the achieved communication range can be made. However, increasing the CCA threshold is not equal to the reduction of the transmit power. A lower transmit power reduces the communication range where the transmitting vehicle may be received. An increased CCA threshold allows for a transmission in case there is already one or more ongoing transmissions in the vicinity. If the vehicle then transmits, the communication range of the other transmitting vehicle(s) is degraded as well. But, vehicles being close to the transmitter will be able to decode its transmission, as we have shown in [18].

As shown in [20], high vehicle density and hence high channel load can easily lead to a significant increase of the

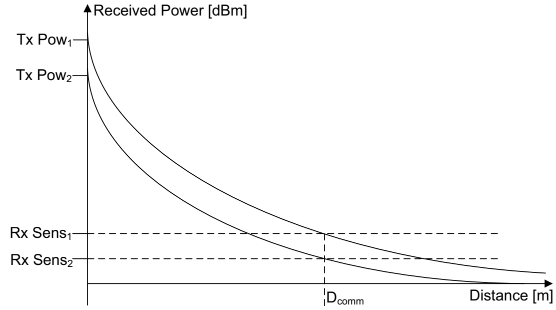

Figure 1: Relation between transmit power and receiver sensitivity: Tx Pow$_1$ and Rx Sens$_1$ achieve same communication range as lower transmit power Tx Pow$_2$ and lower receiver sensitivity Rx Sens$_2$.

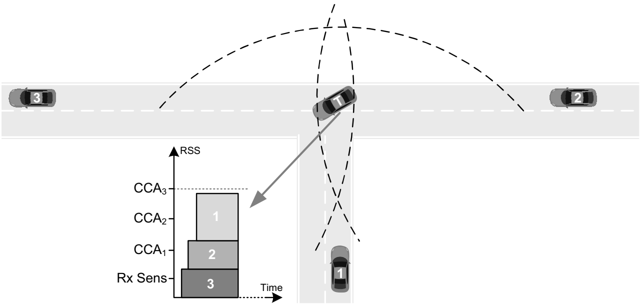

Figure 2: Accumulated signals result in interference at transmitter T. Clear channel only indicated if CCA$_3$ is applied.

medium access delay. This can be due to many vehicles in the vicinity transmitting at the same time, as depicted in Fig. 2. The accumulated signal strength of the overlapping signals does not allow for a detection of an OFDM signal, hence the receiver sensitivity does not apply. According to the standard, the CCA threshold is applied. As depicted, in this situation only an increased CCA threshold (CCA$_3$) would indicate a clear channel.

The study in [20] has shown, the CCA threshold should not be increased arbitrarily. On the one hand, the medium access delay is significantly reduced. On the other hand, the number of packet collisions drastically increases due to more and more hidden stations arising. The study in [20] has further shown that there is no optimal static CCA threshold which provides both, sufficiently low medium access delay and sufficiently low packet loss.

In this paper, we propose a stepwise CCA Threshold Adaptation (CTA) per CAM to be transmitted, depending on the waiting time in the queue. Under high load, this mechanism allows for increasing the spatial reuse and thus limiting the medium access delay of each vehicle. The proposed strategy focuses the communication so that it operates best for safety applications. We define therefore the safety-critical area (up to 100 m around each vehicle), the safety-relevant area ($100 - 300$ m) and the intended communication range ($300 - 1000$ m).

The remainder of this paper is structured as follows. Sec. 2 discusses existing literature on dynamic CCA adaptation. We summarize requirements on advanced carrier sensing and provide suitable metrics in Sec. 3. Sec. 4 describes our approach which is evaluated by a simulation study with the results presented in Sec. 5. We conclude in Sec. 6.

2. RELATED WORK

The problem of local channel congestion is usually tackled by adapting one or multiple transmission-related parameters. In the following, we review approaches that especially consider safety-application requirements as described before. We show that none of the existing congestion-mitigation approaches proposed for VANET scenarios leverages from the dynamic adaptation of the CCA threshold. On the other hand, no existing CCA adaptation approach considers VANETs. We first briefly summarize existing approaches for congestion mitigation in VANETs. Second, we review existing approaches for the adaptation of the CCA threshold.

Torrent-Moreno et al. [21] describe an approach for fair transmit power control in a cooperative way. The distributed algorithm limits the transmit power of each vehicle such that the total load on the communication channel does not exceed a pre-defined threshold.

Rezaei et al. [15] propose a scheme for adapting the message generation rate. The generation of messages is dynamically triggered by locally evaluating the remote position estimation error. If the position estimation based on the previously sent message exceeds a certain error threshold, a new message is generated. This dramatically reduces the load on the communication channel and hence the likeliness of channel congestion. So far, the evaluation of this approach under high channel load is still pending.

A combined approach is presented by Baldessari et al. [1]. The control of the generation rate of CAMs is combined with the adjustment of the transmit power. An estimation of the local vehicle density determines which pairs of transmit power and message rate may be selected. Finally, these pairs are chosen by each vehicle depending on its current situation, e.g. being close to an intersection, a higher message rate would be selected at the expense of a lower transmit power.

Tab. 1 summarizes the differences between the adaptation of transmit power, transmit rate and CCA threshold. The adaptation of each of the parameters provides different methods for the control of the spatial reuse. By adapting the transmit power, the spatial spread of a message can be altered. The transmit rate defines, how often the channel is being accessed and potentially occupied. Changing the CCA threshold allows for controlling the spatial reuse in the time-domain, i.e. when to access the channel. In contrast to the receiver sensitivity, the CCA threshold is only used if no OFDM transmission could be detected which is the under high channel load with presence of hidden stations. Transmit power control demands that vehicles cooperate in the power control which, in turn, demands additional messages. The suitable adaptation of the transmit rate requires measurements of the channel load and/or the current driving situation. Furthermore, transmit power control has to cope with differing (and unpredictable) emitted output power due to temperature variations, aging of the chip or additional exterior equipment like a trailer or a roof rack which significantly attenuates emitted signal. Transmit rate control is challenging with the different requirements given by the various applications. Some demand a high rate whereas others can live with a low rate of messages in the same traffic situation, e.g. lane-merging and forward collision warning on a crowded highway. The CCA threshold adaptation may be limited by the receiver sensitivity which can differ depending on the quality of the chip. Also, the measurement of the CCA threshold can be inaccurate from vehicle to vehicle leading to unfair channel access. Especially the aspect of hardware inaccuracies has not been taken into account so far by any study. However, this is very likely to happen. First, building highly accurate hardware can be very expensive. Second, in existing standards like IEEE802.11 [9], there is no accuracy defined in terms of $\pm X$ dB. Third, inaccuracies could be limited by standards, however misbehavior due to chip aging cannot be prevented by standards. However, the mentioned disadvantages can be tackled and may allow for leveraging significantly from spatial reuse control, especially under high channel load.

	Transmit power	**Transmit rate**	**CCA threshold**
Spatial reuse	Space-domain	Interval of channel usage	Time-domain
Requirements	Cooperativeness, additional information exchange	Needs additional information, e.g. • Channel Busy Time • Driving Situation	None
Challenges	Resulting output power may differ, e.g. because of • Varying temperature • Aging of the chip • Vehicle exterior extras like trailer, roof rack • Uncertainty about varying channel condition	Various applications have different demands, when to set high or low rate	Receiver sensitivities can be different, CCA threshold measurement can be inaccurate

Table 1: Discussion of parameters: Transmit power, transmit rate, CCA threshold

There are several related CCA adaptation schemes proposed for mobile ad hoc networks. Approaches like [22, 23, 24, 25] target an optimal data throughput for unicast communication. However, their results cannot directly be transferred to broadcast communication. Furthermore, no distinction between carrier sensing of OFDM signals and non-OFDM signals (due to multiple interfering signals) is made. For example in [22], only a single carrier sense threshold is considered which translates into some artificial carrier sense range. We argue that the given interference models cannot be applied to VANETs due to the high dynamic in channel condition changes. Furthermore, no special attention has been given to the *reliable broadcast of every single message* as required by active safety applications in VANETs. While these works highlight the usefulness of CCA adaptation in different scenarios, to the best of our knowledge there is no dedicated work on dynamic CCA threshold adaptation for vehicular ad hoc networks.

In [20], we conduct an analysis of available carrier sensing options like different static CCA thresholds and virtual carrier sensing. Concluding, a drastic improvement of reliability can be achieved by the adaptation of the CCA threshold. However, this goes at the expense of an increased medium access delay. Furthermore, no optimal static threshold can be determined that is suitable for both, low and high channel load. The resulting performance is a trade-off between reliability and delay. Also, finding the best trade-off is not a common optimization problem, since the network topology changes are highly dynamic in space and time. Local vehicle densities vary quickly and continuously. Thus, an investigation of a dynamic threshold adaptation is required.

Summarizing, the related work in VANETs mostly alters *how to transmit* while our goal is optimizing *when to transmit* at the last resort. Most approaches base the adaptation algorithms on top of the (local) channel load measurement, i.e. the channel busy time. However, this measurement heavily fluctuates in space as we have shown in [17].

3. REQUIREMENTS AND METRICS

ETSI standards for the Basic Set of Applications (BSA) [5] in combination with the results of the previous section suggest to define dedicated requirements for advanced carrier sensing for VANETs. Subsec. 3.1 derives requirements from the BSA, i.e. applications like *Pre-crash sensing warning* and *Co-operative merging assistance.* Subsec. 3.2 defines appropriate metrics for the performance evaluation to analyze if and to what extent the requirements are met.

3.1 Requirements for Advanced Carrier Sensing

General requirements for carrier sensing in VANETs are stated in [20]: High reliability for every single message, sufficiently high communication range and low message delay. In addition to these requirements, we define requirements for the advanced carrier sensing, targeting proper behavior under high load. As the CCA threshold is mainly responsible under high load, the following requirements apply to the adaptation of the CCA threshold.

- *Scalability of medium access with increasing vehicle density:* First, low medium access delay should be maintained even under high channel load. Second, high reception probability for CAMs in the safety-critical area should be maintained even under high channel load.
- *Fair channel access, even with hardware inaccuracies:* The adaptation of carrier sensing should provide all vehicles with the same chances to access the channel. Even if some vehicles apply different carrier sensing thresholds due to hardware inaccuracies, a compensation of that has to be achieved by a dynamic adaptation.
- *Independence from local channel load measurement:* As the locally measured channel load heavily varies in time and space, carrier sensing should not rely on a local measurement of the channel load.
- *Modularity:* The adaptation of carrier sensing should allow for a combination with other approaches like transmit power control in a framework like [6] to further improve scalability.

3.2 Performance Evaluation Metrics

For the evaluation of the communication system performance, we use the following metrics.

Number of Received CAMs.

Controlling spatial reuse leads either to overlapping transmissions resulting in hidden station problem. To evaluate and compare the severity of packet collisions, we measure the success rate. We define it as the number of successfully decoded CAMs divided by the number of CAMs where the reception has been started, i.e. at least a preamble has been detected. For reasons of comparability, the same data rate must be applied since different data rates have different demands for the minimum SINR.

Message Queue Drops.

If there is a CAM still in the message queue and the successive CAM has already been generated, the previous CAM is obviously outdated and can be dropped. Therefore, we count the total number of dropped CAMs. The impact of dropping a message is supposed to be more significant than a collision in medium access as the latter packet loss does not necessarily concern all vehicles.

Medium Access Delay.

Under high load, the most significant contribution to latency in VANET broadcast communication is the delay in medium access due to a continuous indication of a busy channel. Both, average medium access delay and the cumulative distribution function of the medium access delay have to be considered to evaluate overall performance and fairness.

Awareness Quality.

An integrated metric called Awareness Quality considers the aspects of the aforementioned metrics and their interrelations, as described in [19]. The metric focuses on safety-application requirements in terms of the *lifetime* of the contained information depending on the relative position of the receiver w.r.t. the transmitter. We simplify this to areas around the transmitter: Areas A_k are rings with size

$$A_k = \pi * (a_k^2 - a_{k-1}^2)$$

with area identifier k. Moreover, areas are assumed to be equidistant for simplicity, i.e.

$$a_k = a_1 * k, k \in \mathbb{N}.$$

We can now establish the awareness definition at time T for a certain area k around a certain vehicle n_i as

$$Awareness_k^T(n_i) = \frac{|\mathcal{N}_k^T(n_i)|}{|\mathcal{V}_k^T(n_i)|}$$

with $\mathcal{V}_A$ denoting the set of all vehicles within area k and $\mathcal{N}_A$ denoting the set of all discovered neighbors within area k. Vehicle n_j is a neighbor of n_i within area k at time T,

$$n_j \in \mathcal{N}_k^T(n_i) \Leftrightarrow a_{k-1} \leq \Delta d_{ij} < a_k$$

with $\Delta d_{ij} = dist(n_i, n_j)$ and the area k,

$$T - T_{B-1} < \left\lceil \frac{\Delta d_{ij}}{a_1} \right\rceil t_{kL} + t_{MAC}$$

with $T - T_{B-1}$ the age of the previously received CAM for vehicle n_j located in the k_j-th safety area, determined by $\frac{\Delta d_{ij}}{a_1}$. t_{kL} denotes the respective lifetime of a CAM for vehicle in area A_k. In other words, the age of the previously received CAM must be lower than its *distance-dependent lifetime*, being valid for the safety area where the vehicle is currently located in.[1]

Unawareness.

Complementary to the awareness quality, the unawareness counts the absolute number of unknown vehicles in a certain range, i.e.

$$Unawareness_{A_k}^T(n_i) = |\mathcal{N}_{A_k}^T(n_i)| - |\mathcal{V}_{A_k}^T(n_i) \setminus \mathcal{N}_{A_k}^T(n_i)|$$

This metric will also be used to show the distribution of unawareness among all vehicles. The result of unfair medium access can be evaluated by this means.

4. CCA ADAPTATION

From our analysis in [20], the following conclusions form the basis for the dynamic CCA adaptation.

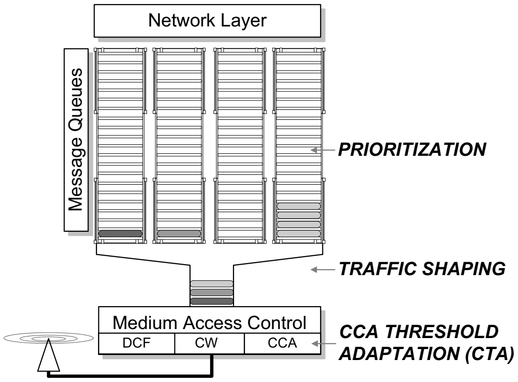

Figure 3: Integration of the proposed mechanisms into existing protocol flow.

- A too high CCA threshold causes strong degradation of the communication range due to hidden stations but keeps the average medium access delay low.
- A too low CCA threshold wastes bandwidth by limiting spatial reuse leading to significant medium access delay but few collisions occur on the channel.
- Due to continuously changing network topology and varying channel conditions there is no optimal static CCA threshold.

As the requirements defined in Sec. 3.1 cannot be addressed solely by *dynamic adaptation of the CCA threshold*, additional mechanisms have to be added to ensure proper operation. Message types with different communication pattern (e.g. event-driven broadcast, connection-oriented unicast) have different requirements and priorities. Their integration into the CCA adaption process demands a *prioritization scheme* and *traffic shaping*.

The integration of these three mechanisms is shown in Fig. 3. The next subsection introduces the stepwise CCA Threshold Adaptation (CTA) as the core idea in this paper. The second subsection describes the prioritization and traffic shaping to achieve proper operation of CTA for CAMs under presence of other other types of data traffic.

4.1 CCA Threshold Adaptation (CTA)

The adaptation of the CCA threshold per message to be transmitted is only applied to the CAMs which is the main cause for high channel load. Seldomly occurring high priority messages like DENMs should get assigned the highest available CCA threshold to achieve the lowest medium access delay.

Fig. 4 depicts the stepwise CCA Threshold Adaptation (CTA). As there may be different qualities of receivers leading to different receiver sensitivities, we do not alter the receiver sensitivity to determine a clear channel. Only the CCA threshold is adapted. The adaptation only depends on the current waiting time. Once a CAM to be transmitted arrives in the message queue at time t_0, the CCA threshold is reset to the default value, i.e. the CCA base threshold. If the CAM is still queued after time t_1, the threshold is increased by an offset. After the increase, CCA should be carried out immediately if the channel is still busy even with the increased threshold. If not, the increase continues after the next time step t_2. Finally, the procedure finishes when either the CAM is sent (reset to base threshold) or dropped since a successive CAM is replacing the previous one (stay at current threshold).

The likeliness of packet collisions increases with increased CCA threshold. To avoid too many collisions, higher CCA thresholds should be applied for a shorter time. Hence, the

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[1] For the sake of brevity, only a shortened description of this metric is given here. For a more detailed explanation and pictorial examples, the reader is kindly referred to [19] where also related measures of awareness are reviewed.

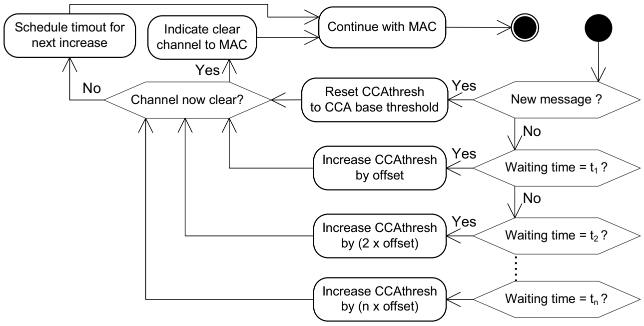

Figure 4: Activity diagram for CTA.

time intervals of the threshold change are exponentially decreasing. As the offset should be defined in dB-steps, the corresponding time-scale should also be logarithmic. For remainder of the paper, we define the interval decrease as follows:

$$t_0 = 0,\ t_1 = \frac{t_B}{2},\ t_2 = \frac{t_1}{2},\ t_n = \frac{t_{n-1}}{2},$$

with t_B being the CAM generation rate. With this increase, the CCA threshold is set highest when all increase intervals have been passed and the message is still queued. The threshold then remains highest until the CAM is sent.

In case the waiting time becomes higher than the generation interval of the CAMs, a suitable queue management rule has to be applied. New CAMs always replace previous CAMs in the message queue. The new one keeps the previous one's position. This is done for two reasons: First, to prevent unnecessary load onto the already loaded communication channel. Such a rule would also not be harmful since the information (e.g. vehicle location) is outdated anyway. Second, newer CAMs should not starve in the queue.

CTA is designed only for the CAMs with each CAM having the same relevance and importance as any other one.

4.2 Prioritization and Traffic Shaping

If different priorities for successive CAMs are defined or if additional messages like DENMs or unicast traffic are considered, priority assignment and traffic shaping have to be employed which additionally control the assignment of CCA thresholds.

CAM priority assignment.

In addition to CTA, different messages have different CCA base thresholds based on their priority. This can be applied if CAMs get assigned different priorities depending on their relevance [12]. If the assignment is not done based on the relevance, another approach can be chosen which is presented in the following.

For CTA, the focus has been to bring every CAM onto the channel. If there are CAMs with a higher importance than others, e.g. occurring periodically within certain time frame like a "key CAM", priorities can be assigned with a logarithmic pattern. This can be achieved using a binary tree with each node representing a priority given by the level. The sequence of priorities can be obtained by a symmetric depth-first traversal. A corresponding binary tree has the following relation to the priority assignment.

Priority assignment	Tree mapping	Formal expression
Number of thresholds	Tree height	l
Priority pattern length	Number of leafs	$2^{l+1} - 1$

The resulting sequence of priorities has the characteristic that messages of the same priority occur within the same time intervals. These reflect intervals where the biggest interval according to the highest priority results in the highest CCA threshold. Hence, this biggest interval of CAMs would always be maintained even under high load. We use the following example to explain the logarithmic threshold mapping. Let us assume a CCA base threshold C_0, an offset of c resulting in $C_1 = C_0 + c$ and two priorities. CAMs are generated with 9 Hz. The resulting CCA threshold pattern would be:

1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
C_0	C_1	C_0	C_0	C_1	C_0	C_0	C_1	C_0

Under high load, it may occur that none of the messages with threshold C_0 can be sent. Only 3 out of 9 CAMs are sent in this case. The benefit of the traversal pattern is that messages of the same priority occur with the same interval. Hence, a minimum CAM interval may be defined for high load.

As shown in Fig. 3, the prioritization takes place in the message queues. The standard IEEE 802.11e [8] defines four message queues. Priority assignment has to consider the mapping to these queues. For example, the usage of 4 or 8 priorities should be used therefore.

Token Bucket Traffic Shaping.

If the system contains data traffic other than CAMs, a traffic shaping mechanism has to be applied. This can be done by using a token bucket scheme which is typically used to prevent bursts of messages. In principle, a token bucket scheme contains a buffer of tokens, the token bucket, with a capacity of N tokens. This token bucket is filled tokens with a rate denoted as R. Each message to be sent "costs" one token which is deleted from the token bucket once the message is sent. If the token bucket is completely filled, it allows for a burst of N messages.

Applied to the threshold adaptation, the token-bucket has to be adapted in a way that different number of tokens are taken from the token bucket depending on the selected CCA threshold. This adaptation prevents that messages are always sent with the highest CCA threshold. Otherwise, the communication becomes severely unstable as shown in [18]. First, the higher the CCA threshold the higher the number of required tokens. Second, the given priority should be considered. Each priority has a corresponding default CCA threshold with corresponding default cost. For each next higher CCA threshold, the cost should be higher, e.g. doubled. For the next lower CCA threshold, the cost should be lower, e.g. halved. An example is shown in the following table. Four CCA thresholds are available and four priorities assigned by the application. The default cost for the corresponding CCA threshold is 8 tokens. The table shows the number of tokens required for mapping of message priority to CCA threshold:

	CCA threshold			
	Highest	**High**	**Low**	**Lowest**
Prio 0	8	4	2	1
Prio 1	16	8	4	2
Prio 2	32	16	8	4
Prio 3	64	32	16	8

A transmitting station has to retrieve tokens from the token bucket so that the CCA returns a clear channel. Tokens are then removed from the token bucket when a suitable CCA threshold is set and the message is finally transmitted. To avoid that a low priority message blocks a high priority message, all incoming messages are sorted by priority so that high priority messages are processed first (and transmitted first since they need fewer tokens for high CCA thresholds).

To ease the integration into the existing prioritization scheme defined in IEEE 802.11e [8], the described token bucket procedure should occur on top of the message queues defined in IEEE 802.11e.

4.3 Discussion of CCA adaptation

The core of the CCA threshold adaptation is the stepwise CCA threshold adaptation (CTA). To allow a fully integrated approach, we apply traffic shaping and a prioritization scheme. In the following evaluation of the approach, we will focus on the CCA threshold increase only. The rationale behind this is the high periodicity of CAMs leading to the problem of local congestion. Additional rare messages like DENMs do not significantly increase the channel load. The differences in the results are expected to be negligible. Furthermore, it is assumed that vehicles generate as many tokens such that no CAM must be degraded in its assigned CCA threshold. Hence, no traffic shaping needs to take place.

5. PERFORMANCE EVALUATION

The performance evaluation compares CTA with different static CCA thresholds. We consider therefore different scenarios of vehicle density, especially high vehicle density. First, it is to be investigated how our approach improves the performance under high load Second, it has to be ensured that the performance under low load is not degraded compared to static thresholds.

Modeling VANETs accurately involves a very high number of variables covering aspects from both, communication domain and road traffic domain. Neither a mathematical model nor a measurement campaign with manageable effort are suitable means for our performance evaluation of high channel load and high vehicle density. Therefore, we investigate the performance of CTA by a simulation study.

For the communication part, the commonly used network simulator JiST/SWANS [3, 2] has been applied. VANET specific components are based on the extension of the Ulm University [4]. We conform to commonly used parameters for simulating VANETs. They are summarized in Tab. 2. The data rate is set to 6 MBit/s according to [10]. For the two-slope log-normal shadowing, we apply $\rho_1 = 1.8$ and $\rho_2 = 2.8$ [11, 14] whereas ρ_2 is valid from an average NLOS distance of 50 m on. The deviation for the normal distribution is $\sigma = 3$.

The Awareness Quality metric is measured in intervals of 100 m, with a tolerated MAC delay of 50 ms. The resulting lifetimes are $150, 250, \ldots, 1050$ ms for $A_1, A_2, \ldots, A_n$, respectively.

5.1 Simulation scenario

We employed SuMo (Simulation of Urban Mobility [13]) to generate movement traces of vehicles driving on high-speed motorways in order to get realistic changes of the network topology. Two German motorways are used: The four-lane A9 and the two-lane A92, both located in the north of Munich. The extracted area has a size of 8×8 km. Within this area, subareas of 1×1 km serve for collection of results, as shown in the following table.

Scenario	Section	Avg Density	Avg Speed
Low	A92 MUC	75 veh/km^2	40 m/s^2
Medium	AK Neufahrn	166 veh/km^2	33 m/s^2
High	AK Neufahrn	260 veh/km^2	30 m/s^2

One subarea (A92 Munich airport) includes only the A92, the other one covers the motorway junction (AK Neufahrn). The subareas are named by their resulting channel load, i.e. *low* for low channel load, and *medium*, *high*, respectively.

5.2 Simulation results

In the following, we evaluate the performance of CTA and compare it against different static CCA thresholds. A comparison to other congestion control approaches is not done. On the one hand, CTA is meant to be a supplementary approach supplementary approach to be used in addition to transmit power and rate control. On the other hand, as discussed in Sec. 2, other approaches like rate or power control cannot be compared since they have different objectives. For example, with a lower CAM rate, requirements of certain applications cannot be met anymore. Decreasing the transmit power can lead to link outages due to shadowing by other large vehicles like trucks, as measured by Gallagher et al. [7].

Fixed Parameter	**Value**
Simulation time	60 seconds
Confidence interval	99%
Number of runs	8
Path loss model	2-slope log-normal shadowing
Fading model	Rayleigh fading
Transmit power	20 dBm
Carrier/Receiver SINR	5/8 dB
Signal propagation delay	LOS distance-based
CAM generation jitter	±1 ms
Noise/Interference model	Thermal/Accum. avg power
Maximum communication range	≈ 1 km
MAC-Layer protocol	IEEE P802.11p
AIFS (AC_BK)	9
Contention window	15 slots
Data rate	6 MBit/s
CAM rate	10 Hz
CAM length	350 Bytes
Safety critical area A_1	100 m
Neighbor lifetime (A_1)	150 ms
Field size	8 km × 8 km
Mobility and road model	SuMo-generated traces
Varied Parameters	**Values**
Traffic densities	47 - 273 veh./km^2
Velocities	80 - 250 km/h
Threshold increase offsets	6, 12, 18 dB
Number of threshold increases	3
Threshold increase intervals	50, 25, 12.5 msec

Table 2: Simulation parameters overview

5.2.1 *Low and Medium Channel Load*

The results for low and medium channel load are jointly shown in this section. Each result corresponds to the 99% confidence interval based on 8 simulation runs each. Under low channel load, no significant interference occurs, as depicted in Fig. 5a). The lowest static CCA threshold (-95 dBm) provides the best awareness quality. Especially at higher distances, less hidden stations occur and thus fewer packet collisions. The differences become most significant at $500 - 600$ m with around $20 - 30\%$. At the lowest distance of 100 m, only a slight difference can be observed which is due to the rarely occurring simultaneous transmissions [22]. Summarizing, the results from the low load scenario serve as a reference: For low vehicle density and/or low penetration rate, a low CCA threshold should be applied.

A slight reduction of the awareness quality can be observed under medium channel load compared to low channel load. In Fig. 5b), the difference in the awareness quality in particular at the lowest distances $(100, 200$ m$)$ become more significant. Due to increased medium access delay, the good performance of the -95 dBm static CCA threshold is degraded. In this scenario for the safety-relevant area $(100 - 300$ m$)$, a static threshold of -85 dBm performs best.

We now enable CTA on top of the previously best performing base threshold of -95 dBm. The results of the awareness quality with CTA enabled is depicted[2] in Fig. 6. It can be seen that already in medium density, a slight increase of the awareness quality in the safety-critical area (100 m) can be achieved by the increase of the CCA threshold in steps of 12 dB.

5.2.2 *High Channel Load*

Fig. 7 depicts the results for the awareness quality using

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[2] The results for the increase of 6 and 18 dB are omitted for the sake of readability since the graphs are close to each other.

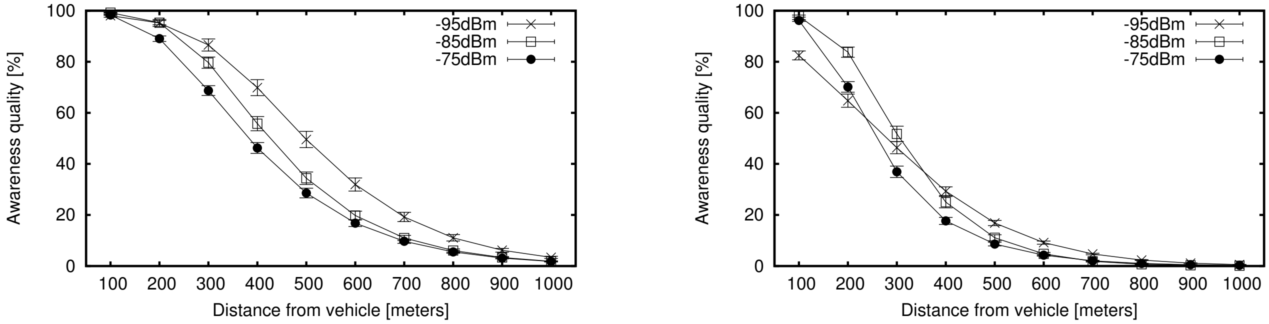

Figure 5: Awareness quality for static CCA thresholds in a) low channel load and b) medium channel load.

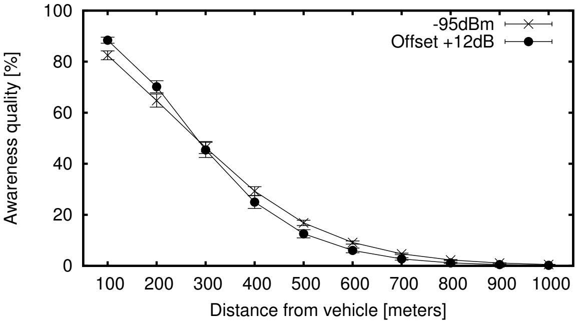

Figure 6: Awareness quality with CTA enabled (Base -95dBm) in medium channel load.

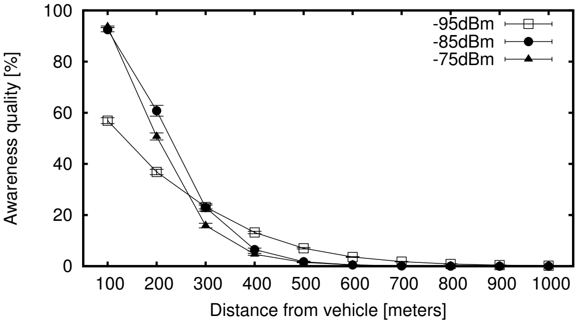

Figure 7: Awareness quality for static CCA thresholds in high channel load.

static CCA thresholds. The trend of reduction of the awareness quality in the safety-critical area continues. The reduction is more than 40% for a static threshold of −95 dBm compared to a static threshold of −85 dBm.

In accordance with the previous section, we apply CTA to the lowest CCA threshold −95 dBm. The corresponding simulation results are presented Fig. 8a). The reduction of the awareness can be compensated by CTA. Considering the result for 100 and 200 m, an offset of 12 dB performs best. Beyond this distance, a degradation of the awareness quality has to be accepted due to more packet collisions resulting from the increased CCA threshold.

For comparison, the results for a base threshold of −85 dBm are shown in Fig. 8b). One can see that no increase of the awareness is achieved. The reason is that the medium access delay stays low. No increase of the CCA threshold takes place.

From these two figures, the load-dependent engagement of CTA can be seen. Only if the medium access delay becomes high, the CCA threshold is increased. This shows that the awareness quality is increased in an intended way within the safety-critical area whereas the degradation of awareness in the area beyond has to be accepted. In other words, the ability to dynamically control the spatial reuse is achieved by CTA.

	-95dBm	**+6dB**	**+12dB**	**+18dB**	**-85dBm**
Drops	16625	1367	0	0	1

Table 3: Average number of message queue drops for base thresholds -95 dBm, -85 dBm and CTA enabled with different offsets in the high load scenario.

In the following, we analyze in more detail, where the identified increases and decreases originate from. We therefore look at the average medium access delay, its cumulative distribution, the number of message drops as well as the success rates.

The average delay is shown in Fig. 9a). For a static threshold of −95 dBm, the average delay is around 50 msec. If the CTA is enabled, the average value even slightly increases, especially for the offset of +6 dB. The average delay for −85 dBm is below 10 msec which shows that CTA does not frequently engage. To better understand the slight increases of the average medium access delay, we show the cumulative distribution of occurred medium access delays in Fig. 9b).

For the static threshold −95 dBm, the graph shows a shallow increase of the cumulated medium access delays occurred in the simulation. The medium access delays are nearly equally distributed in the interval of 20 to 80 msec. 20% of the delays are close to 0 msec. The graph also indicates that only 80% of the medium access delays are below 100 msec. The remaining CAMs are dropped, i.e. replaced by the newly arriving CAMs. The number of dropped CAMs can be found in Tab. 3. For a static threshold of −85 dBm, nearly no drops occur since all the medium access delays are below 40 msec (a cumulative occurrence of ≈ 100%). The results for CTA nicely show each increase step. An offset of +18 dB per increase step has the most significant occurrence of medium access delays of 50 msec. For +12 dB, around 25% of the medium access delays are within 50 and 70 msec. The slowest reduction of the occurred medium access delays is achieved with the lowest offset of +6 dB per step. It can also be seen that the second increase step occurs quite often which is displayed by the behavior of the graph between 70 and 80 msec.

Fig. 10 presents the total number of received CAMs by all vehicles in the simulation. Again, the performance of the lowest CCA threshold −95 dBm is low but comparable with the performance of the highest CCA threshold −65 dBm. The packet losses due to message queue drops (−95) result in the same degradation as the packet collisions due to hidden stations (−65). However, with CTA enabled, the total number of received CAMs is increased (base threshold −95 dBm)

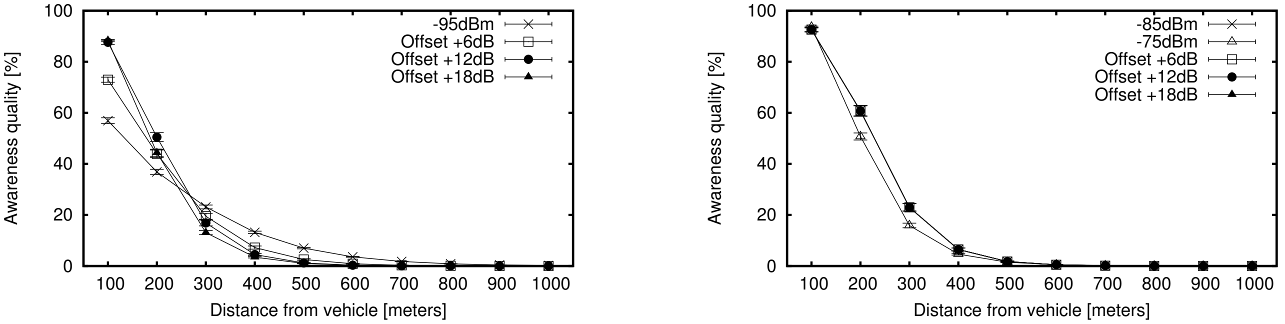

Figure 8: Awareness quality with CTA enabled, Base -95 dBm and -85 dBm, under high channel load.

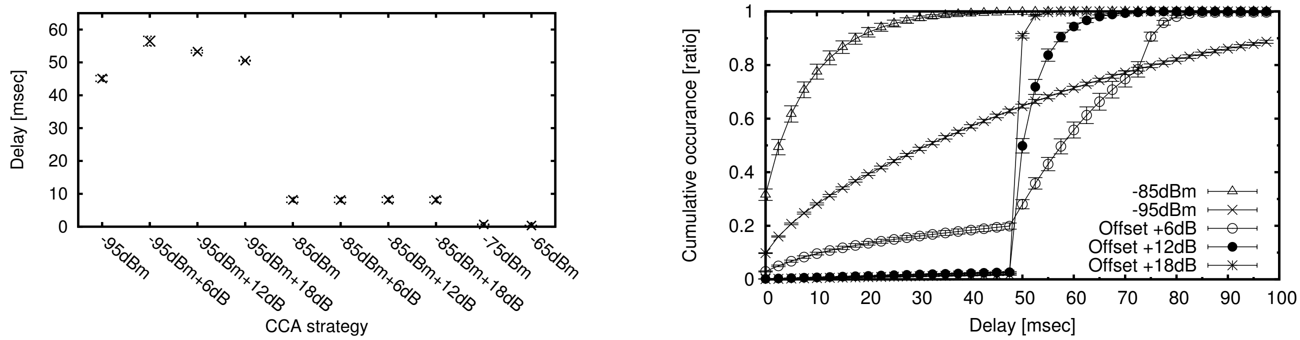

Figure 9: Average medium access delay a) and cumulative distribution b) for -95 dBm base CCA threshold.

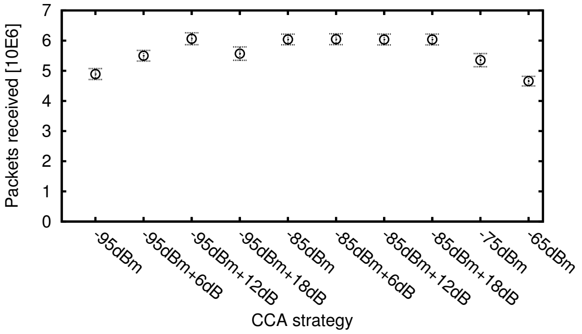

Figure 10: Number of received CAMs in Millions.

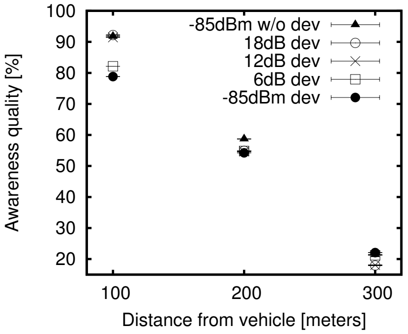

Figure 11: Awareness quality for 100, 200, and 300 meters under inaccuracies of the CCA threshold.

to the same value as the static threshold −85 dBm using the offset of +12 dB.

5.2.3 Inaccurate CCA thresholds

Significant inaccuracies in the measurement of the CCA threshold inevitably lead to unfair channel access among the vehicles. For example, a vehicle that actually measures −76 dBm instead of −85 dBm is always preferred in medium access compared to a vehicle that actually measures −94 dBm instead of −85 dBm. To demonstrate that CTA can compensate this unfairness, we randomly set the CCA threshold. The following results consider an equal distribution of ±9 dB around the base threshold.

Fig. 11 compares the awareness quality for a base CCA threshold of −85 dBm. For a reference, the awareness for accurate CCA thresholds is shown as *-85 dBm w/o dev* for −85 dBm without enabling the deviations of the thresholds. Especially, in the safety-critical distance of 100 m, a difference of more than 10% in the awareness quality can be observed. The reason for the degradation is that single vehicles are unable to access the medium several times, resulting in message drops. Enabling CTA allows for mitigating this degradation. As a result, the awareness is nearly same value as if a vehicles have an accurate CCA with a static threshold −85 dBm. Thus, CTA enables the unprivileged vehicles to overcome the unfairness and access the medium after the threshold increase.

This is confirmed by the results of the number of message queue drops, depicted in Tab. 4. Without hardware inaccuracies, no drops occur. However, with hardware inaccuracies and a static threshold of −85 dBm, 22196 CAMs are dropped before sending. The table further shows that for a sufficiently high offset of +12 dB per step, the drops are significantly reduced.

As presumed before, few vehicles are unknown to surrounding vehicles due to inability to access the channel in high density. This is supported by the results of the unawareness per vehicle. Fig. 12 presents the reduction of the unawareness per vehicle at 100 m around each vehicle. This

	-85dBm	+6dB	+12dB	+18dB
Drops	22196	17203	143	0

Table 4: Number of message queue drops under inaccuracies of the CCA threshold.

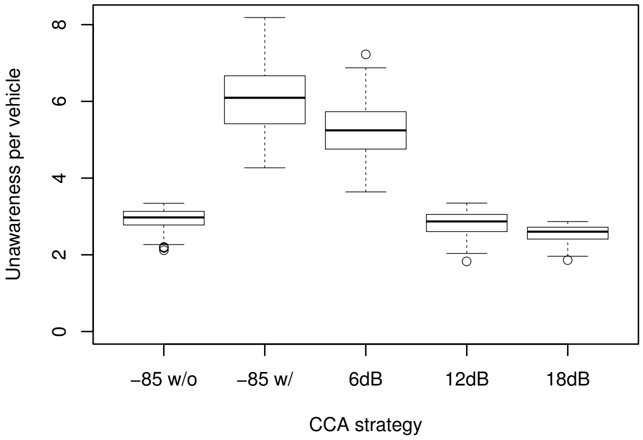

Figure 12: Awareness quality under inaccuracies of the CCA threshold.

box-and-whisker plot[3] firstly presents a significant increase of the unawareness if there are inaccuracies, comparing *-85 w/o* and *-85 w/*. On average, twice the number of vehicles is unknown inside the safety-critical area. These vehicles are those with the highest disadvantageous inaccuracy. They have to drop most of their CAMs. Enabling CTA mitigates this unfairness if the offset of CTA is set sufficiently high (12 dB), i.e. higher than the most inaccurate CCA threshold setting (9 dB). Secondly, the figure shows the reduction of statistical spread of the unawareness among the vehicles. The first quartile, median, and third quartile are much closer to each other if CTA is enabled with an offset of 12 dB. Most notably is the decrease of the maximum values (upper whisker). An unawareness of $4-8$ unknown vehicles at 100 meters is reduced to $2-3$ unknown vehicles averaged over time. The respective distribution is similar to the distribution if no hardware inaccuracies occur.

5.3 Discussion of Simulation Results

Under low channel load, a low static CCA threshold provides the best performance. The medium access delay is negligible and the high sensitivity lets the vehicles sense the channel very carefully to avoid hidden stations. Under medium load, a reduction of the awareness occurs in the most safety-critical area of 100 meters if a low CCA threshold is applied.

Especially under high channel load, the degradation of the awareness quality is severe. A higher static CCA threshold should then be applied to provide better performance. However, it provides least performance under low channel load/penetration rate which is not desirable.

Therefore, we proposed and investigated the stepwise CCA Threshold Adaptation (CTA) based on packet waiting times. We summarize the major findings in Fig. 13. Significant improvements can be achieved especially under high load within the safety-critical area, depicted in Fig. 13a). Thus, CTA allows to combine the good performance of a low CCA threshold under low load and sufficient awareness under high channel load which may be limited in time and occur seldomly. However, the benefits at low distances go at the expense of the awareness quality achieved in higher distances, as shown in Fig. 13b).

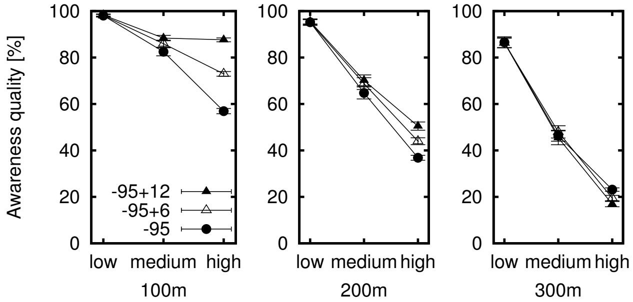

Figure 13: Summary of awareness quality for 100, 200, and 300 meters safety area, for all three scenarios, base threshold -95dBm and CTA with offset +6dB and +12dB.

As CTA does not engage under low load, an unintended degradation of the awareness does not occur under low load. Only under high load, the lower awareness in higher distances is traded against a higher awareness in lower distances. Thus, CTA is a suitable approach to control the spatial reuse according to the VANET safety-related requirements.

Significant inaccuracies in the measurement of the CCA threshold can lead to unfair medium access. Even for the well-performing threshold of −85 dBm, a degradation of the awareness quality can be observed. Some vehicles do not get access to medium under high load since they always apply a lower CCA threshold than others. Hence, a significant number of packet drops occurs. This can be mitigated, if CTA is enabled. Furthermore, the parameter of the offset should be set higher than the assumed inaccuracies.

All in all, CTA allows for sending and receiving the required 10 CAMs per second even under high vehicle density. Hence, the requirements of applications like Co-operative merging assistance [5] are satisfied in low *and* high vehicle density.

6. CONCLUSIONS

Depending on the CCA threshold, the communication performance in VANETs can be significantly degraded. The standardized threshold is too high and results in too many packet collisions. By setting a low CCA threshold like −95 dBm, the reliability under low channel load can be significantly increased. However, when doing so the medium access delay rises and results in a high number of packet drops under high load. We have demonstrated this effect in simulations and quantified the resulting performance degradation by suitable metrics like the awareness quality and unawareness per vehicle. The degradation even concerns the reception from vehicles being at closer distances. To counter this degradation under high load, we presented an approach to increase the CCA threshold depending on local message waiting times to focus the communication to the most safety-critical area. Simulation results show that this significantly improves the medium access control and in particular the carrier sensing to meet the requirements of VANETs. We showed how this solution performs better than static thresholds over a broader range of scenarios. Even under high vehicle density and hence high channel load, CTA allows for limiting the medium access delay in parallel with a high number of successfully received CAMs. Furthermore, by a dedicated metric called awareness quality, we were able to demonstrate that CTA shows the following characteristics:

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[3] Each respective x-value consists of the box, indicating the first quartile, median, and third quartile. Additionally, the whiskers show the minimum and maximum values. If these values are greater than 1.5 times the interquartile range, each probe is indicated by a circle.

- Increase vehicles' awareness within most safety-critical area even under high channel load.
- Significantly reduce the medium access delay under high load.
- No degradation of performance under low channel load.
- No exchange of control information, i.e. an isolated approach.
- Mitigation of unfairness in channel access due to hardware inaccuracies and different receiver sensitivities.
- Prevention of transmitter-blocking due to external interference.

With the prevention of local congestion and the improved spatial reuse of the communication channel, the presented approach improves scalability of the CSMA/CA medium access scheme especially for VANET scenarios. Due to its simplicity, the approach is robust and can easily be implemented. Moreover, it is independent of channel load measures and channel load thresholds but leverages from controllable spatial reuse of the wireless channel.

CTA is becoming part of the framework for decentralized congestion control [16], ratified as ETSI TS 102 687 [6]. In future work, we will compare our approach with existing approaches for transmit power control and data rate adaptation schemes. Also, we will investigate the beneficial combinations of the CCA adaptation in parallel with the adaptation of other transmit-related parameters.

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