Analysis and Design of Effective and Low-Overhead Transmission Power Control for VANETs

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ABSTRACT

The control of vehicles' radio communication behavior to deal with the constrained available wireless bandwidth has been identified as a key challenge in VANETs. As an element of congestion control, this paper addresses distributed transmission power control as a means to control the impact of periodic transmissions ('beacons') on the overall channel load. By also considering recently discussed fairness issues, we first examine the trade-off between the effectiveness of controlling the channel load on the one hand and the corresponding costs in terms of the required packet overhead on the other hand. We provide insights to the underlying estimation problems and present a sensitivity analysis with respect to non-homogeneous vehicular traffic densities and non-perfect channel conditions. Second, based on the analysis, we propose a segment-based power adjustment approach based on a distributed vehicle density estimation. The approach put forward in this paper reduces overhead by two orders of magnitude compared to previous approaches while still being effective in controlling the channel load.

Categories and Subject Descriptors: C.2.1[Network Architecture and Design]: Wireless communication, Distributed Networks; I.6.3 [Simulation and Modeling]: Applications

General Terms: Design, Performance.

Keywords: Analysis, transmission power control, congestion control, VANETs, wireless vehicular communication.

*F. Schmidt-Eisenlohr acknowledges the support of Deutsche Forschungsgemeinschaft (German Research Foundation) within the Research Training Group GRK 1194 'Self-organizing Sensor-Actuator-Networks'.

†J. Härri acknowledges the support of the Ministry of Science, Research and the Arts of Baden-Württemberg (Az: Zu 33-827.377/19,20) and Klaus Tschira Stiftung for the research group on Traffic Telematics.

VANET'08, September 15, 2008, San Francisco, California, USA.

1. INTRODUCTION

Road safety has been a long-term endeavor for public authorities, automobile industry and researchers worldwide. The rapid evolution of wireless communication technology and its significant cost reduction in recent years have opened a new door to traffic safety through *Vehicular Ad Hoc Networks (VANETs)*. Radio-equipped vehicles are assumed to directly exchange information and, thus, to exceed the boundaries of locally available knowledge. Distributed safety applications running in each vehicle are thereby envisioned to assist the driver by making use of the enhanced information set.

From a communication perspective, VANETs have to ensure that the communication traffic generated by the sending vehicles can be served by the wireless medium. For traffic safety it is assumed that each vehicle will proactively send out periodic one-hop messages (called beacons) to establish mutual awareness. In addition, when a hazardous situation is detected, 'reactive' or 'event-driven' emergency messages will be send out. Without controlling the vehicles' communication behavior, one can easily be confronted with stressed and saturated channel conditions simply due to the transmissions of periodic messages. Hence, one needs to control the load or the share of the channel imposed by the periodic messages to allow for reliable and low-latency transmissions of high-priority emergency messages. While in a TDMA-based approach one would reserve specific slots for high-priority data [1], it is less straightforward to 'guarantee' a certain bandwidth for emergency messages in an IEEE 802.11 CSMA-based approach as we assume it for our work. In this paper we address the issue of how to keep the beaconing load at a preconfigured (constant) level in an IEEE 802.11-based VANET.

In general, the channel conditions in the network have to be observed in order to adjust the vehicles' communication behavior to the varying vehicular traffic densities. To measure the condition of the wireless network, researchers have proposed several metrics: channel load [2], channel busy time [3, 4] or vehicular traffic density [5, 6], to name a few. By applying *congestion control* mechanisms, communicating nodes aim in a cooperative manner to avoid congested channel situations with respect to some chosen metrics. The impact on the wireless channel can be controlled, for example, by adjusting packet sizes, transmission powers or transmission rates. To understand how the 'autonomous' transmissions of the vehicles affect the conditions of the wireless network at a specific geographic location A, vehicles not located at A but potentially affecting the network at that location need to obtain information from other vehicles to estimate the corresponding network conditions at A. Thus, for an 'informed' estimation, packet overhead will be introduced which, at a first sight, looks counterproductive for the goal of helping an already stressed medium. Therefore, a careful analysis is required with respect to the minimum overhead that is needed for effective congestion control.

In this paper we focus on transmission power control strategies to control the beaconing load on the channel. We fix packet size and transmission rate and build our investigation on the channel load metric to quantify channel conditions. We present the following contributions:

- We analyze the minimum 'required knowledge' of positional information on neighboring nodes that is necessary to guarantee a preconfigured maximum beaconing load in the network.
- We analyze how well the beaconing load can be controlled when the distributed control is challenged by realistic (Nakagami-m) channel models as well as by non-homogeneous vehicular traffic densities.
- We propose an effective beacon power control approach that only requires a negligible amount of additional communication overhead.

The remaining part of this paper is structured as follows: in Section 2 we present related work on congestion control and introduce essential notions. In Section 3 the impact of information accuracy on controlling the beaconing load is studied analytically and via simulation. Based on the drawn conclusions we present in Section 4 a power control approach that effectively controls the channel load with a negligible amount of overhead. In Section 5 we illustrate the impact and benefits of our solution. We conclude our work in Section 6.

2. BACKGROUND

We first describe related work and define essential notions that will be used throughout this paper. In addition, we describe the power control algorithm that will serve as a reference in our study.

2.1 Related work in congestion control

The objective of congestion control in VANETs is to maintain a sufficient channel availability to successfully deliver safety messages with a high probability. Any transmission on the wireless medium affects the channel and thus should be carefully regulated. In VANETs, there are two types of transmission: 'event-driven' messages such as the transmission of safety messages, and 'periodic beacons' notably used for mutual awareness.

Transmitting event-driven messages without using a congestion control mechanism creates the well known *broadcast storm* problem. Being not specific to VANETs, congestion control of event-driven messages has been widely studied in the past for MANETs or Sensor and Actuator Networks (SANETs), and *Topology Management* solutions or efficient broadcasting techniques have been proposed. When an event-driven message needs to be broadcasted and relayed by the network, the general idea is to limit the number of potential relays to a minimal but sufficient set, therefore limiting the level of unnecessary channel load. Surveys of available efficient broadcasting solutions for MANETs and SANETs may be found in [7–10], while some recent work on their adaptations to VANETs may be found in [6, 11, 12]. As an important part of the channel congestion in VANETs comes from the transmission of beacon messages, we focus this paper on improving beacon congestion control. Solutions provided in [6–12] for event-driven congestion control do unfortunately not represent feasible solutions to the challenges addressed in this paper.

When considering periodic transmissions of beacon messages, *beacon congestion control* contains three degrees of freedom: beacon packet size, beacon transmission rate, or beacon transmission power. As constraining or artificially reducing a beacon packet size is practically unsustainable in VANETs, power control and transmission rate are the two essential levers of beacon congestion control[1].

The first basic mechanism that alters the transmission rate is located at the IEEE 802.11p MAC layer, which is part of the protocol stack *IEEE Wireless Access for Vehicular Environment (WAVE)* [13]. It contains a basic *QoS* functionality, which optionally blocks any low priority transmission attempt when the wireless channel occupancy time is higher than 50 %. Unfortunately, this node-centric feature is not sufficient to efficiently control potential congestion on the wireless medium. Other solutions have been developed at the network layer [3, 4, 6], where the common idea is to limit the time-based utilization of the wireless medium only to the transmission of the necessary application-based information. A survey dedicated to congestion control mostly oriented to transmission rate adaptation may also be found in [14].

Adapting the transmission power has also been subject to various studies as a method to limit the spatial perturbation of the wireless medium. In literature, it may also be found under the term *transmission power control* or *topology control*. According to Santi [15], transmission power control techniques cannot be considered as 'topology control' if they do not reach a network-wide perspective based on a coordinated action. Since the network-wide perspective under study in this paper being an optimal channel load for which a coordinated decision is required, we will focus our study on topology control strategies. Transmission power control solutions such as [16–19] are therefore not sufficient for our objective.

The most comprehensible source of information related to topology control is given by Santi [15], who described many different approaches such as LMST, CBTC, DistRNG, KNeigh, or XTC, to name only a few. Yet, the network-wide perspective targeted by most of these protocols is connectivity.

Other approaches [20–23] illustrated that optimal network performance could not be reached by solely considering connectivity, and suggested to also take into account transmission load or interference levels. These initial attempts illustrate that optimal congestion control depends on more than just connectivity.

A major limitation in most of the previous works in topology control was that the topology was static or quasi-static, an issue that would disqualify any solution for VANETs.

[1]In the rest of this paper, we will use the term 'Congestion Control' in the sense of *Beacon* Congestion Control.

One first attempt at considering topology control for VANETs has been proposed by Artimy *et al.* [5], where transmission ranges are dynamically adapted to the rapidly changing vehicular topology. Another solution proposed by Torrent-Moreno *et al.* was to consider a fair sharing of the bandwidth as the network-wide perspective, but with a dynamism and overhead that would be adapted to vehicular environment. The algorithm called FPAV [2] has been proven to be formally correct, and was later extended to a distributed environment with the name D-FPAV [24]. The authors illustrated that a desired channel quality could be guaranteed in the whole network and that wireless bandwidth can be shared among vehicles in a fair manner. Finally, Khorakhum *et al.* [4] proposed to perform a power control assignment based on a network-wide desired *channel busy time* as wireless channel quality. When the channel busy time is higher or below than a desired threshold, a coordinated decision is taken on the action to be conducted.

In this paper, our objective is to study the minimal requirements to effectively control the maximum beaconing load on the channel. We will therefore study a topology control solution that considers the adaptation of the transmission power for beacon messages. Our work is based on the previously discussed D-FPAV algorithm. In the next sections, we are going to define the basic concepts behind this protocol and then provide a short description of its functionality.

2.2 Used terms and concepts

We briefly introduce the basic terms and concepts that are used throughout this paper. They are considered for idealistic conditions, but we will illustrate that our conclusions hold in less idealistic conditions as well.

The Carrier Sense Range of a node v using a transmission power p_v (CSR(v, p_v)) is the maximum distance up to which a node w is able to distinguish a transmission triggered by node v from the background noise on the wireless medium. The Carrier Sense Maximum Range (CSR$_{max}(v)$) is the carrier sense range of node v considered with its maximum allowed transmission power p_{max}.

The Carrier Sense Area of a node v using power p_v (CSA (v, p_v)) is an abstract concept representing a circle centered at v spanned by CSR(v, p_v). Similarly, the CSA$_{max}(v)$ is the carrier sense area of node v spanned by its CSR$_{max}(v)$.

The Channel Load [2] for a vehicle v at a time t is the summed load in *bits/sec* created by all transmissions initiated by any node w, for which node v would belong to CSA(w, p_w) at time t. It is a metric of the quality of the channel and a portray of the wireless communication's reliability.

The Beaconing Load [2] represents the Channel Load created by the transmission of beacons. The **Maximum Beaconing Load (MBL)** defines a threshold controlling a desired level of beaconing load. By setting the MBL to e.g. 2.0 or 2.5 Mbps (for a 3 Mbps channel), a portion of the bandwidth is reserved for other data traffic such as the dissemination of safety messages.

2.3 Recap of the D-FPAV protocol

The basic idea behind the Distributed Fair Power Control (D-FPAV) [24] protocol is to apply transmission power control in a wireless environment based on the following optimization constraints:

- Limit the beaconing load to a network-wide maximum beaconing load (MBL) to 'reserve' bandwidth for the transmission of event-driven messages.
- Share the bandwidth used by beacons between nodes in a fair manner.
- Maximize the beacon transmission power to improve the knowledge of the neighborhood without violating the MBL and fairness constraints.

We will start recapitulating D-FPAV[2] by looking at a single vehicle v, assuming that it has a global view on the environment.

On a simplified level, the FPAV algorithm adjusts the transmission power as follows: for every beacon message, the transmission power of all surrounding vehicles is 'virtually' increased step-by-step (starting at lowest possible power level) while estimating the resulting beaconing load at each vehicle after each step. As long as the MBL is not violated for any vehicle and the maximum allowed transmission power has not been reached, power levels are further increased. After FPAV has finished, the highest transmission power level which did not violate the MBL parameter is taken for the transmission of the beacon message.

As described above, the decision of when to stop increasing the transmission power is based on the estimation of the beaconing loads. Thus, the effectiveness of FPAV with respect to the MBL constraint depends on the accuracy of the load estimation. According to Torrent-Moreno *et al.* the beaconing load of a vehicle v is calculated by

$$BL_v = \sum_{w \in W} s_w \cdot r_w \ \ [bits/sec]$$

where W denotes the set of vehicles containing v in their carrier sense area and s_w and r_w the beacon size and the transmission rate of vehicle w.

Now, when applying FPAV in a distributed environment where no global view is possible, the load estimation is more challenging and its accuracy heavily depends on the knowledge of surrounding vehicles' position and communication behavior. In addition, due to the fact that the beaconing load of vehicle v is influenced by all messages which can be sensed by v, the estimation has to consider even vehicles outside the communication range. Since one-hop beacon broadcast is inherently unable to provide an awareness beyond the communication range, it is inevitable to invest additional communication overhead to obtain that awareness. Due to this reason, the authors of D-FPAV introduce so called *extended beacon messages*, which are piggybacked every n beacon messages and contain the list of the positions of all vehicles located inside $CSA_{max}(v)$ as estimated by vehicle v. How often extended beacons have to be sent and whether including all vehicles inside $CSA_{max}(v)$ is crucial is subject to a trade-off between desired estimation accuracy and acceptable extra communication effort. The analysis of this trade-off is one of the contributions of this paper and is discussed in Section 3. Note that the additional communication effort has to be distinguished from traditional multi-hop forwarding strategies, since the effort is made only to support the accuracy of the load estimation process.

Finally, we emphasize that the precision of the transmission power, and thus the beaconing load, also depends on

[2]We only briefly introduce D-FPAV here and refer the reader to [24] for a more detailed description of this protocol.

the granularity of the transmission power steps. The latest IEEE WAVE compliant wireless cards support a power step granularity of 0.5 dBm. The maximum number of power steps available to D-FPAV therefore depends on the maximum allowed transmission power, which may be different for each country.

3. SENSITIVITY ANALYSIS

In the previous section we pointed out that D-FPAV relies on the *knowledge of the positions and the communication behavior of surrounding vehicles*. Moreover, its performance heavily depends on the extent and the accuracy of that knowledge. For instance, being aware of only half of all surrounding vehicles might be insufficient to achieve a network-wide MBL. While moving towards a complete and accurate knowledge will help to ensure a strict MBL compliance, the invested overhead will increase, resulting in a decreased effectiveness. Thus, a trade-off exists between overhead and accuracy. The following subsections elaborate on the raised issues by means of a theoretical worst case analysis and trade-off study using simulations. Our analysis also considers the impact of adverse situations such as non-homogeneous vehicular traffic densities and probabilistic radio channel conditions.

3.1 Worst case analysis

The following theoretical consideration takes the perspective of any arbitrarily chosen reference vehicle v and inspects its required knowledge in order to determine whether its own transmission will exceed the MBL threshold at any surrounding vehicle. Figure 1 supports the analysis and shows a straight road on which 4 vehicles u, v, w and y are depicted by small dots. In addition, the carrier sense areas $CSA(v, p_v)$ and $CSA(w, p_w)$ are illustrated by circles around the vehicles v and w.

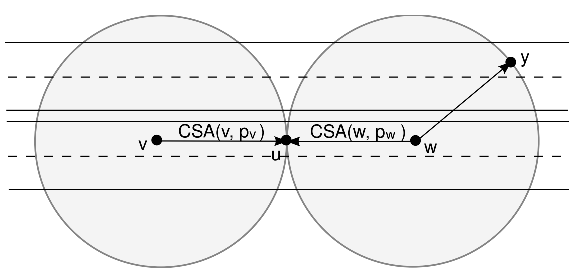


Figure 1: Basic scenario illustrating the required knowledge a vehicle v has to possess in order to adjust its power with respect to the MBL.

According to the definitions in Section 2.2, a transmission of v using a power p_v will increase the beaconing load at vehicle u since it is located inside $\text{CSA}(v, p_v)$. However, the beaconing load observed by vehicle u also depends on the communication behavior of vehicle w because $\text{CSA}(w, p_w)$ covers u as well. Thus, in order to adjust the transmission power and still respect the MBL threshold, the reference vehicle v has to be aware of the positions of vehicles u and w. In a worst case situation, where all vehicles use the maximum allowed power, the required knowledge corresponds to an awareness of a circular area with radius $2 \times \text{CSR}_{max}(v)$.

Parameter	Value
Frequency	5.9 GHz
Data rate	3 Mbps
Carrier Sense Threshold	-96 dBm
Noise floor	-99 dBm
SINR for preamble capture	4 dB
SINR for frame body capture	10 dB
Slot time	16 μs
SIFS time	32 μs
Preamble length	40 μs
PLCP header length	8 μs

Table 1: Medium access and physical layer configuration parameters for IEEE 802.11p

Yet, apart from knowing the positions of vehicles w and u, vehicle v further needs to know their current communication behavior, for instance average beacon size and transmission ratio. If the generated beacon load of each vehicle is constant, this knowledge is implicitly available. However, in case of D-FPAV the generated beacon load of e.g. w is not a priori known due to the extended beacon messages. Since extended beacons carry a list of positions of neighboring vehicles, the size of an extended beacon sent by vehicle w depends on the number of vehicles inside $\text{CSA}_{max}(w)$. In our example vehicle u and y are located inside $\text{CSA}_{max}(w)$, whereas only u is within a distance of $2 \times \text{CSR}_{max}(v)$. Therefore, in order to correctly estimate the generated load of w, the awareness of vehicle v has to cover $\text{CSA}_{max}(w)$ as well. In a worst case, this corresponds to a knowledge up to a distance of $3 \times \text{CSR}_{max}(v)$.

3.2 Simulation setup and scenarios

In this section we study the trade-off between the communication overhead and the accuracy of the provided knowledge on the positions of neighboring vehicles. In particular we want to determine up to which extent positional information about surrounding vehicles is necessary to achieve a network-wide MBL. Therefore we use the network simulator ns-2.31 [25] and add modules that implement the behavior of D-FPAV. We also use an overhauled MAC/PHY-model [26], adapted to the specifics of the envisioned standard for inter-vehicle communications, IEEE 802.11p, Table 1 lists the configuration parameters of the medium access and physical layer according to the IEEE 802.11p draft standard.

In order to evaluate the theoretical results of Section 3.1, we consider two different variants of extended beacons. With the *full overhead* variant, positional information on the vehicles within CSA_{max} of v is included in extended beacons, whereas with *reduced overhead* only vehicles within $\text{CSA}(v, p_v)$ are considered; p_v being the adjusted transmission power of v. Additionally, we address the impact of available knowledge on the performance of the D-FPAV algorithm. Therefore, we artificially reduce a vehicle's available information set, referred to as *considered information range (CIR)*, to one (1060 m) or two (2120 m) CSR_{max}, respectively.

Independent of the simulated variant and CIR, D-FPAV is configured as follows: every vehicle is transmitting 10 beacon messages per second with a size of 500 bytes each. Once per second an extended beacon is sent. 32 discrete power steps are used, ranging from a minimum of -10.23 dBm to a maximum of 17.95 dBm, including the antenna gains. Such discretization is necessary from a technical point of view,

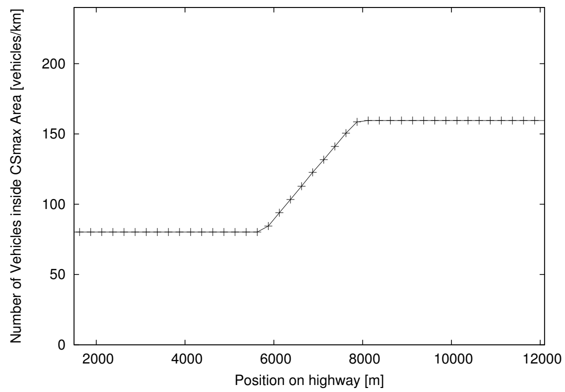


Figure 2: Scenario layout: highway scenario with static vehicles and different regions of interest: uniform distribution of vehicles (low-density and high-density) and an inhomogeneous transitional area at position 7000 m.

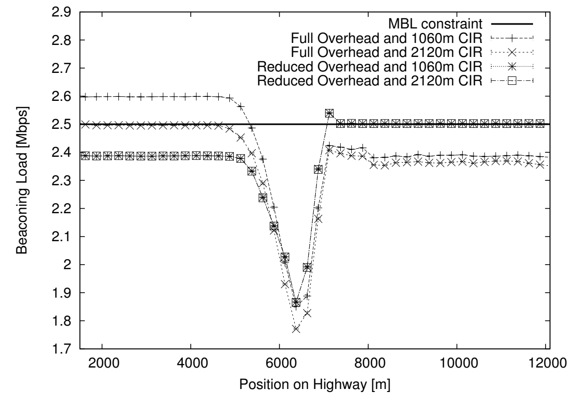


Figure 3: Beaconing load in the scenario with full and reduced overhead and Two-Ray Ground radio propagation. The considered information in D-FPAV is limited to ranges of 1060 or 2120 m.

but also affects the power control algorithm, as we will see later in Section 3.3.

The simulations are run using the deterministic Two-Ray Ground propagation model. Yet not being realistic, we thus facilitate comparison to the protocol behavior of FPAV that assumes deterministic radio propagation. As we are aware of the limitations of deterministic radio models simulations are as well conducted using the probabilistic Nakagami-m fading model [27]. It has been shown to suitably resemble the real radio conditions on highways [28]. For further details we refer to the discussion on the impact of simplified assumptions in Section 3.4. Every single simulation is run for 30 seeds [3]. The simulation time is set to 15 s and the first second of each simulation is skipped in the evaluation to ignore artificial effects of the starting period.

In the analysis we determine the minimum amount of knowledge or overhead, respectively, necessary to control transmit power, namely to keep the beaconing load below a preconfigured MBL threshold of 2.5 Mbps. Therefore, we set up a scenario that is as simple as possible while yet revealing the important aspects for power control. We incorporate several regions of interest that allow an independent analysis of different typical conditions. Figure 2 shows the scenario layout: for each position x on a highway the number of vehicles located within CSA_{max} around position x is shown.

The leftmost and rightmost area of the scenario reflect a static uniform distribution of vehicles, with a *low-density area* in the left and a *high-density area* in the right. Assuming a highway with 2 lanes per driving direction these areas represent vehicular traffic with 40 respectively 80 vehicles per km. In the center of the scenario the vehicle density shifts from low- to high-density at road position 7000 m (*transitional area*). This transitional region is presented to explore the most crucial situation for power control mechanisms, that is, a change of traffic densities.

3.3 Effectiveness and overhead analysis

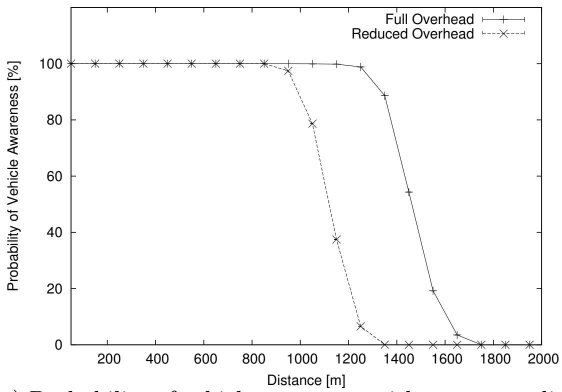
First, we inspect the observed beaconing loads in Figure 3 with respect to the different communication overheads and the different ranges up to which vehicles are considered in D-FPAV. In the homogeneous regions of the scenario, we can see the same steady beaconing load for each vehicle that is located sufficiently far away from the transitional area. If we look at this transitional area at the center of the scenario, we notice that the load drops down significantly and increases again if we move further to the high-density region. In some situations, however, the configured MBL threshold is obviously violated.

We first focus on homogeneous traffic densities for the full and reduced overhead variants both taking two CSR_{max} (2120 m) into account. Obviously, the full overhead variant matches the MBL value in the low-density area while keeping below in the high-density area. Similarly, the reduced overhead variant mostly agrees with the MBL threshold in high densities and falls below in low traffic densities. Here, our simulation results expose the influence of discrete power levels: both curves below the MBL threshold correspond to an optimal configuration as an increased power level would (slightly) violate the MBL restriction.

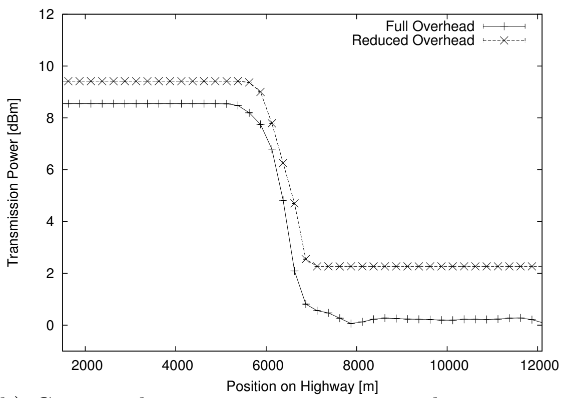
Discrete power levels are also important when applying the theoretical results from Section 3.1. As can be seen in Figure 4(b) the (maximum) transmission powers in the low-density area correspond to a CSR of 614 m (8.5 dBm) and 651 m (9.5 dBm) for the full and reduced scenario, respectively. Obviously, the configured CIR of 2120 m easily covers these (maximum) CSRs more than three times and even more easily the obtained knowledge up to approximately 1400 m and 1100 m (cf. Figure 4(a)). Thus we do not cut off the obtained knowledge. However, the obtained knowledge does not cover the required 3 (maximum) CSRs. The impact on the resulting beaconing load is therefore most significant for the low overhead variant resulting in an apparent violation of the MBL (cf. Figure 3), and marginal in the full overhead variant. Note that the full overhead variant cannot provide sufficient information to cover the required knowledge either, but as described above, the discrete steps of power levels compensate the minor lack of knowledge and cause adherence of the MBL threshold.

The impact of discrete power levels decreases when the difference between required and obtained knowledge becomes sufficiently large. This can be demonstrated by reducing

[3]Figures 3, 4(a), 4(b), 6, 8(a) and 8(b) contain 95 % confidence intervals, though they are hard to recognize in the figures.



(a) Probability of vehicle awareness with respect to distance. Reference vehicle placed at highway position 3800 m.



(b) Computed transmission powers with respect to highway positions

Figure 4: Impact of different vehicle densities and different overhead used to obtained information about a vehicle's surrounding and the computed transmission powers with respect to highway position. For the computation D-FPAV considered vehicles up to a distance of 2120 m.

the CIR to 1060 m. While the reduced overhead variant is hardly affected, vehicles in the full overhead variant lose approximately 20 % of knowledge (cf. Figure 4(a)). The result is illustrated in Figure 3: whereas the experienced load using the reduced variant is not visibly affected, the full overhead variant now underestimates the communication traffic, thus computing higher transmission powers and thereby exceeding the MBL threshold in the low-density area. The significantly lower chosen transmission powers in the high-density area (partly) compensate the CIR restriction.

The explanation for the significant beacon load drop at the beginning of the transitional area is given by Figure 4(b): the steady increase of vehicle density between the position of 6000 m and 8000 m requires reduced transmission powers, compared to vehicles in the middle of the low-density area. While this is necessary to guarantee a MBL at the beginning of the high-density area, it leads to unused bandwidth in the transitional area. Continuing the discussion with respect to required overhead, we can also see that the reduced overhead variant is not able to provide sufficient knowledge in transitional areas to prevent slight MBL violations (cf. Figure 3).

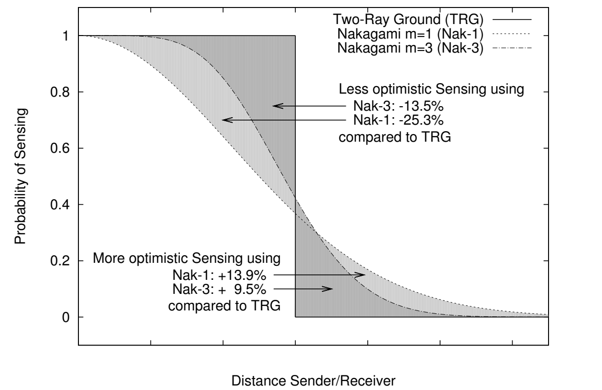


Figure 5: Comparison of the probability of sensing (with respect to the distance) of more realistic radio propagation models and Two-Ray Ground. The shaded areas illustrate the differences between Nakagami and Two-Ray Ground, normalized to the rectangular sensing area of Two-Ray Ground.

3.4 Influence of radio propagation

Up to now, deterministic Two-Ray Ground propagation was used in all presented results. In this section we address the impact of more realistic propagation models on the presented power control approach. D-FPAV bases its calculations on Two-Ray Ground, independently from the existing real-world conditions. Consequently, if propagation follows the Nakagami model, the actual probability of sensing is less optimistic than assumed by Two-Ray Ground within its carrier sense range, as illustrated by the shaded areas in Figure 5. Thus, the number of affected vehicles is overestimated by D-FPAV. Beyond Two-Ray Ground's carrier sense range, the behavior is vice versa. In total, a comparison of the over- and underestimation leads to a global overestimation.

Figure 6 shows the beaconing load under Nakagami and Two-Ray Ground radio propagation with respect to the position on the highway. It is observable that the beaconing load experienced with Nakagami clearly stays below MBL due to the load estimation based on Two-Ray Ground.

4. LOW OVERHEAD TRANSMISSION POWER CONTROL

The required knowledge of positional information, which is necessary in order to ensure a MBL threshold, can be obtained on different ways. In the previous section we analyzed a power control strategy which provides this knowledge by forwarding status information of surrounding vehicles every n beacon messages, yet with a significant overhead. According to the simulation results in Section 3.3, a reduction of overhead is possible by only forwarding status information of vehicles from the close surrounding. However, the introduced overhead is still not negligible. According to Santi's guidelines to building topology control protocols adapted to mobile environments ([15], p.144), the overhead could be further reduced by using relatively 'low-quality' information to build the topology.

Hence, we propose a distributed vehicle density estimation strategy in Section 4.1 to provide an approximation of the surrounding traffic situation to each vehicle. This approximation is then locally used by a separate power control

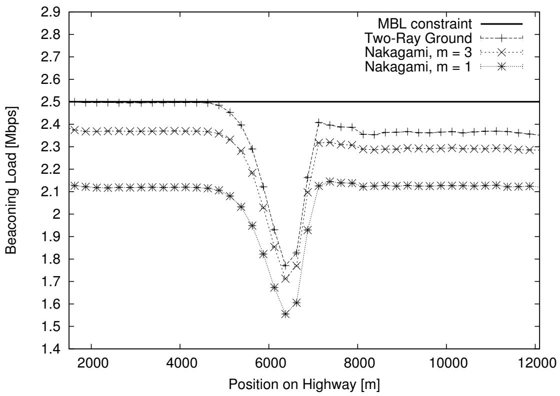


Figure 6: Beaconing load when using full overhead under Nakagami and Two-Ray Ground radio propagation. The considered information in D-FPAV is limited to 2120 m.

policy, presented in Section 4.2. Since this approach is based on 'macroscopic' densities instead of 'microscopic' positions, the policy can not ensure a strict MBL. Nevertheless, we will show later that only a slight violation of the MBL has to be accepted. In both proposals we consider a set of vehicles $V = \{v_1, \ldots, v_n\}$ moving along a straight road, sending periodic beacon messages using fixed transmission rate and fixed message size.

4.1 Distributed vehicle density estimation

In the following, we propose the *Distributed Vehicle Density Estimation* protocol DVDE which provides an approximate knowledge of the surrounding traffic situation up to two carrier sense ranges to each vehicle. Subject to the DVDE protocol are the following three definitions.

Definition 4.1 (Vehicle Environment). *Given a set of vehicles $V = \{v_1, \ldots, v_n\}$, a maximum transmission power p_{max} and any vehicle $v_i \in V$, the environment of vehicle v_i, denoted as $E(v_i)$, is the intersection of the deterministic carrier sense area of vehicle v_i at power p_{max} and the shape of the considered road.*

Definition 4.2 (Environment Partition). *Given a vehicle environment $E(v_i)$ and an odd resolution parameter r, the partition $E(v_i, r)$ is the division of $E(v_i)$ into r equally sized segments. Additionally, we denote segments from $-(r-1)/2$ up to $(r-1)/2$, whereas positive numbers are given to segments in driving direction and negative numbers to segments in the opposite direction. The segment number 0 is reserved for the segment which is aligned around the reference vehicle.*

Definition 4.3 (Vehicle Density Histogram). *Given a vehicle environment partition $E(v_i, r)$, the vehicle density histogram of vehicle v_i is specified by*

$$VDH(E(v_i, r)) = \left\{ S_i(j) \;\middle|\; j = -\frac{r-1}{2}, \ldots, \frac{r-1}{2} \right\}$$

where $S_i(j)$ is the number of vehicles located inside segment j of $E(v_i, r)$.

The first definition simply describes the area from which a vehicle can be influenced. The area is denoted as the environment of a vehicle and is basically a spatial restriction of the general concept of a deterministic circular carrier sense area with respect to vehicular highway scenarios. The latter two definitions split the environment into equally sized segments and specify a vehicle density histogram over the entire environment by counting the number of vehicles in each segment.

Based on the information included in received beacons, each vehicle is able to locally derive a vehicle density histogram of its own environment. In order to approximate the vehicular traffic densities in a distributed manner, each vehicle will periodically broadcast a derived histogram, which reflects the current vehicles' view on the densities in the surrounding. Similar to extended beacons in D-FPAV, this histogram is piggybacked every n beacon messages. Thereby, each vehicle is able to maintain a collection of vehicle density histograms derived by itself and its direct neighbors. This collection of histograms is finally merged according to the following (simple) policy: i) the accuracy of the computed vehicle density for a particular segment j is best if done by the vehicle closest to the center of segment j. Therefore the density value is taken from the histogram of the vehicle closest to the center of the segment ii) if the segment alignment of the closest vehicle does not match the alignment of that particular segment, the histogram of the closest vehicle has to be shifted accordingly iii) if shifting is required, the density values of the histogram are linearly interpolated. By merging the collection of histograms, each vehicle is able to approximate the existing traffic densities beyond its communication range and even beyond the border of its own vehicle density histogram.

Merging is either performed after the reception of a new histogram or on application request, e.g. every time a congestion control policy has to access the approximated traffic densities. Note, that the approximation is further improved if vehicles exchange a histogram which is derived from the merged approximation instead of the one locally derived.

In comparison to D-FPAV, the illustrated approach reduces additional communication overhead and, as shown later in Section 5, provides sufficient knowledge to apply MBL-aware power control. In particular, the overhead scales with the number of segments but not with the number of vehicles. Furthermore, this approach allows to control the granularity of the obtained knowledge by using small or large resolution parameters for the partitioning.

4.2 Segment-based Power Adjustment for Vehicular environments (SPAV)

The obtained approximation of the surrounding network topology is used by a second protocol proposal SPAV, to (cooperatively) adjust the transmission power of vehicles. In principle, SPAV is executed locally at each vehicle in order to compute a common maximum transmission power for all vehicles in its environment. Therefore, SPAV derives a so called catchment area for each segment in its environment partition using the merged vehicle density histogram provided by DVDE.

Definition 4.4 (Catchment Area). *Given a vehicle density histogram $VDH(E(v_i, r))$ of a vehicle $v_i \in V$, the catchment area of a segment j is defined as the maximum area, in which vehicles are allowed to transmit beacons with a maximum common power p, such that transmissions only by these vehicles affect the center of segment j without violating j's MBL threshold.*

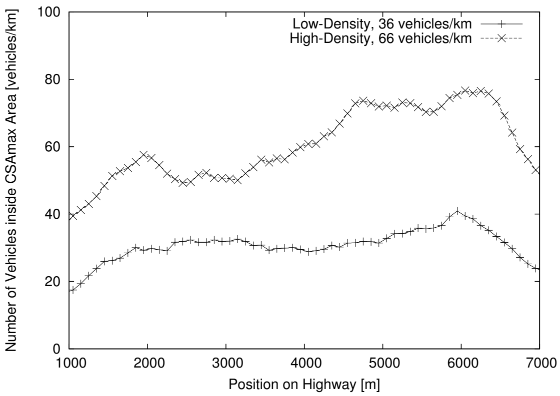


Figure 7: Underlying vehicle densities of the evaluated scenarios with respect to the position on the highway.

The following consideration supports the interpretation of Definition 4.4: from a safety perspective it is most important to favor information from vehicles in the close surrounding over information from vehicles at further distances. Thus, we are interested in the maximum surrounding, for which the cumulative load generated by all vehicles inside this area is lower than the allowed MBL threshold.

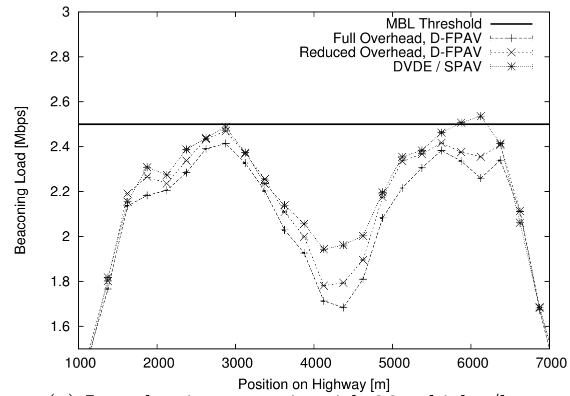
Therefore, in order to adjust the transmission power with respect to a MBL threshold, any vehicle $v_i \in V$ will derive the catchment areas of all segments within its environment $E(v_i)$ and select the transmission power p which corresponds to the minimum catchment area observed in $E(v_i)$.

5. COMPARISON OF DVDE/SPAV AND D-FPAV

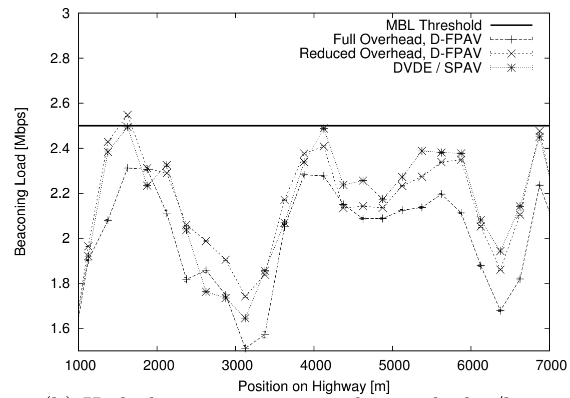
We will now evaluate the performance of DVDE in combination with SPAV and compare the results to D-FPAV using the same metrics as in Section 3. Again we use ns-2.31 for our simulations and configure the MAC/PHY model according to the values listed in Table 1. In order to investigate and compare the protocols in realistic scenarios, we extracted a scenario out of the FleetNet Movement Patterns [29]. It models a 6 km bidirectional highway with 3 lanes per direction and shows average vehicle densities of 66 vehicles/km. The vehicle density with respect to the position on the highway is illustrated in Figure 7, labeled *High-Density*. For completeness reasons our comparison also considers a scenario having a low traffic density of 36 vehicles/km, labeled *Low-Density*.

In our comparison, we configure DVDE to use a resolution parameter of 21 segments and piggyback the merged vehicle density histogram every 10 beacon messages, whereas we assume that the encoding of the histogram requires 1 additional byte per segment. Similarly, we configure D-FPAV to deliver an extended beacon every 10 times as well and distinguish between full and reduced overhead. As in Section 3.2 we will configure the wireless channel to reflect Two-Ray Ground propagation. All remaining parameters are set to the same values as described in Section 3.

Figure 8 illustrates the experienced beaconing loads with respect to the position on the highway for DVDE/SPAV and D-FPAV. We can see that all strategies provide similar results, whereas a strict compliance with the MBL threshold



(a) Low-density scenario with 36 vehicles/km



(b) High-density scenario with 66 vehicles/km

Figure 8: Experienced beaconing loads in low and high density scenarios using either DVDE/SPAV or D-FPAV (with full and reduced overhead) and a configured MBL of 2.5 Mbps.

is only achieved by D-FPAV. In case of DVDE/SPAV the MBL is slightly exceeded.

Regarding overhead, DVDE/SPAV only generates a negligible amount of additional communication overhead as illustrated in Table 2. Indeed, the simulation results show that DVDE/SPAV requires only 0.42 % additional communication overhead, independent of the present traffic density, whereas D-FPAV requires already 16.20 % or rather 22.80 % additional overhead in the low density scenario. In case of high vehicle densities D-FPAV with full overhead requires 41.40 % additional communication.

The communication overhead that is saved by DVDE has two benefits: on the one hand vehicles may choose higher transmission powers without violating the MBL compared to D-FPAV. Thereby, beacons from farther distances may be received. On the other hand, it is possible to achieve similar

	Low density	High density
D-FPAV full overhead	22.8%	41.4%
D-FPAV reduced overhead	16.2%	18.6%
DVDE/SPAV	0.42 %	0.42 %

Table 2: Overhead related to a beaconing of 10 beacon messages per second, each with a size of 500 bytes.

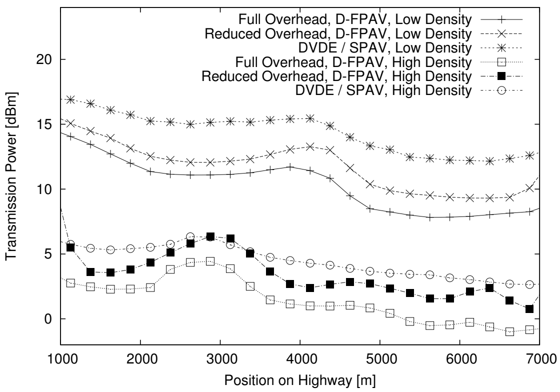


Figure 9: Computed transmission powers of DVDE/SPAV and D-FPAV with respect to highway position.

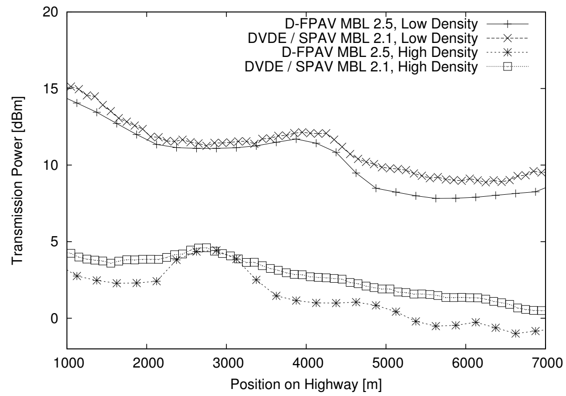


Figure 10: When using the DVDE/SPAV approach even a preconfigured MBL of 2.1 allows higher transmission powers compared to D-FPAV for an MBL of 2.5.

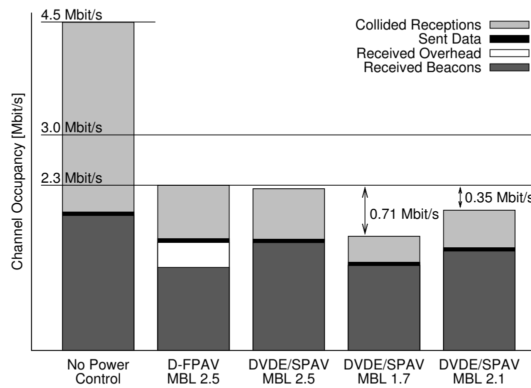


Figure 11: Channel occupancy without power control, with D-FPAV, and with different configurations of DVDE/SPAV.

transmission powers even with a reduced MBL value. Addressing the first benefit, we observe in Figure 9 that, when keeping the same MBL, the lower overhead of DVDE/SPAV allows a higher transmission power to be used by each vehicle in the scenarios. In contrast, in Figure 10 we show results when adapting the MBL so that similar transmission powers are obtained. Here, DVDE/SPAV configured with a reduced MBL of 2.1 Mbps outperforms D-FPAV configured with 2.5 Mbps in terms of achievable transmission power of each node. Thus, we can 'save' about 0.4 Mbps of bandwidth for other applications without observing any negative influence on the level of awareness given by the beacon messages. Consequently, the bandwidth kept available for event-driven safety messages increases by 80 % in this configuration.

We further emphasize the impact of saving bandwidth on the channel by looking at Figure 11. It shows the channel occupancy for a reference vehicle in the *High Density* scenario driving on the highway in the region around 1750 m. We compare configurations without any power control, with D-FPAV, and with DVDE/SPAV under different configurations of the MBL value. The leftmost bar shows channel occupancy without any power control algorithm: note, that in case of collisions all colliding packets are counted as load, thus, the available channel bandwidth of 3 Mbps is exceeded due to collisions.

The second bar indicates the bandwidth usage for D-FPAV and an MBL of 2.5 Mbps. The total load remains below the defined MBL and approximately half of it actually contains information from received beacons. Some bandwidth has to be used to carry the overhead of extended beacons, while only a small amount is taken for own transmissions. Yet, a considerable amount of bandwidth is lost for beacon messages that were not received successfully due to packet collisions. In contrast to the scenario without any power control, we are able to keep a reserved bandwidth for dissemination of emergency messages.

The third bar allows direct comparison to DVDE/SPAV with the same MBL, 2.5 Mbps. It is clearly visible that, due to the reduced overhead, a significantly greater amount of channel load contains information from received beacons. While the same amount of packet collisions occur only very little (even not visible) overhead information is received. Clearly, due to the MBL configuration, nearly the same amount of channel load is occupied.

Finally, the two rightmost bars show the impact on channel usage when reducing the MBL for DVDE/SPAV to either 1.7 Mbps that corresponds to the same amount of successfully received beacons as D-FPAV at 2.5 Mbps, or to 2.1 Mbps that maintains a similar transmission power as D-FPAV at 2.5 Mbps. We observe the load that is now saved and which can be reserved for event-driven emergency messages.

To summarize, we have shown that DVDE/SPAV as a beacon power control approach with reduced overhead has potential to improve channel usage, which can be beneficial, for example, for other applications like emergency warning dissemination.

6. CONCLUSIONS

Transmission power control has been identified as a key parameter to counter channel congestion caused by transmission of beacon messages. In this paper we analyzed distributed strategies that control the vehicles' communication behavior in a cooperative manner to keep the beaconing load below a preconfigured threshold. We showed that in order to guarantee a network-wide beaconing load threshold, precise positional information is necessary up to three times a node's maximum communication range, a conclusion that remains valid regardless of the propagation model or the distribution of traffic density. In VANETs, the overhead created by the gathering of such detailed information, however, does not scale. We therefore studied the impact of reducing the scope and accuracy of positional information on the beaconing load control approach. In addition, we studied the impact of non-homogeneous vehicular traffic densities and non-perfect channel conditions on the effectiveness of the beaconing load control. We clearly observed that *i)* in a non-homogeneous traffic density scenario not all of the bandwidth available for beaconing can be exploited due to fairness reasons, and *ii)* that under 'non-perfect' channel conditions the beaconing load is likely to be overestimated when no corrective actions are taken.

Finally, we showed that the overhead of the existing D-FPAV approach can be reduced but still scales linearly with the number of nodes within carrier sense range. We then put forward a segment-based power adjustment procedure and demonstrated that by slightly relaxing the strict compliance to a network-wide beaconing load threshold, we were able to design an efficient transmission power strategy with a negligible overhead. With segment-based power adjustment the overhead is independent of the number of nodes. The gain in effectiveness can be used to reduce the bandwidth needs of beacon messages while maintaining the same level of information. The gained bandwidth is now available for other applications, e.g., for event-driven messages. Our future work will address joint rate and power control as well as the use of prediction to reduce channel load.

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