Vehicle-to-Vehicle Communication: Fair Transmit Power Control for Safety-Critical Information

Marc Torrent-Moreno, Jens Mittag, *Student Member, IEEE*, Paolo Santi, and Hannes Hartenstein, *Member, IEEE*

***Abstract*—Direct radio-based vehicle-to-vehicle communication can help prevent accidents by providing accurate and up-to-date local status and hazard information to the driver. In this paper, we assume that two types of messages are used for traffic safety-related communication: 1) Periodic messages ("beacons") that are sent by all vehicles to inform their neighbors about their current status (i.e., position) and 2) event-driven messages that are sent whenever a hazard has been detected. In IEEE 802.11 distributed-coordination-function-based vehicular networks, interferences and packet collisions can lead to the failure of the reception of safety-critical information, in particular when the beaconing load leads to an almost-saturated channel, as it could easily happen in many critical vehicular traffic conditions. In this paper, we demonstrate the importance of transmit power control to avoid saturated channel conditions and ensure the best use of the channel for safety-related purposes. We propose a distributed transmit power control method based on a strict fairness criterion, i.e., distributed fair power adjustment for vehicular environments (D-FPAV), to control the load of periodic messages on the channel. The benefits are twofold: 1) The bandwidth is made available for higher priority data like dissemination of warnings, and 2) beacons from different vehicles are treated with "equal rights," and therefore, the best possible reception under the available bandwidth constraints is ensured. We formally prove the fairness of the proposed approach. Then, we make use of the ns-2 simulator that was significantly enhanced by realistic highway mobility patterns, improved radio propagation, receiver models, and the IEEE 802.11p specifications to show the beneficial impact of D-FPAV for safety-related communications. We finally put forward a method, i.e., emergency message dissemination for vehicular environments (EMDV), for fast and effective multihop information dissemination of event-driven messages and show that EMDV benefits of the beaconing load control provided by D-FPAV with respect to both probability of reception and latency.**

***Index Terms*—Active safety, contention, fairness, information dissemination, power control, vehicle-to-vehicle communication.**

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M. Torrent-Moreno was with the Institute of Telematics, University of Karlsruhe, 76131 Karlsruhe, Germany. He is now with Advanced Automotive Communications®, a joint venture of Ficosa and GMV, 08028 Barcelona, Spain (e-mail: marc.torrent.moreno@gmail.com).

J. Mittag is with the Decentralized Systems and Network Services Research Group, Karlsruhe Institute of Technology, 76124 Karlsruhe, Germany (e-mail: jens.mittag@kit.edu).

P. Santi is with the Instituto di Informatica e Telematica del Consiglio Nazionale delle Ricerche, 56124 Pisa, Italy (e-mail: paolo.santi@iit.cnr.it).

H. Hartenstein is with the Steinbuch Centre of Computing, Karlsruhe Institute of Technology, 76128 Karlsruhe, Germany (e-mail: hartenstein@kit.edu).

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I. Introduction

DIRECT vehicle-to-vehicle communication based on radio technologies represents a key component for improving safety on the road. Various public and private organizations worldwide are funding national and international initiatives that are devoted to vehicular networks, such as the InternetITS Consortium [1] in Japan, the Vehicle Infrastructure Integration (VII) Initiative [2] in the U.S., the Car2Car Communication Consortium (C2CCC) [3] in Europe, and the Network on Wheels (NoW) Project [4] in Germany. Currently, the IEEE 802.11p Working Group [5] is developing a standard that is based on carrier-sense multiple access (CSMA) and tailored to vehicular environments. The effort is assisted by initiatives from various parts of the globe.

Direct radio-based vehicle-to-vehicle communication can provide a fundamental support to improve active safety, i.e., accident prevention, by making information available beyond the driver's (or other car sensor's, e.g., radar) knowledge with almost minimal latency. Note that active safety is composed of *sensing* and *communication* activities. In this paper, we are concerned with active-safety-related communications.

When considering safety-related communication, two types of messages can be identified: 1) *periodic* and 2) *event driven*. Periodic exchange of "status" messages that contain the vehicle's position, speed, etc. (also called *beacons* in the following discussion) can be used by safety applications to detect potentially dangerous situations for the driver (e.g., a highway entrance with poor visibility). It is assumed that every equipped vehicle will also contain a global navigation satellite system (GNSS), e.g., Global Positioning System (GPS), to determine its absolute position. On the other hand, when an abnormal condition (e.g., an airbag explosion) or an imminent peril is detected by a vehicle, an event-driven message (also called *emergency message* in the following discussion) is generated and disseminated through parts of the vehicular network with the highest priority.

While, from a safety perspective, one key challenge for direct vehicle-to-vehicle communication technologies in the market introduction phase will be to achieve a significant penetration rate of equipped vehicles, it will be even more challenging in fully deployed high-density vehicular scenarios due to the high data load on the channel solely caused by beaconing. With CSMA, a high load on the channel is likely to result in an increased amount of packet collisions and, consequently, in a decreased "safety level," as seen by the active-safety application. In particular, beacon messages will not successfully be decoded, even when sent by a nearby vehicle, and event-driven

messages will show a slow unreliable dissemination process. To counter the issue of channel saturation, we proposed to make use of packet-level interference management based on per-packet transmit power control to give packets "relative" weights that control the introduced interferences and, implicitly, the ability to capture packets.

In this paper, we analyze vehicle-to-vehicle communication from an active-safety perspective and identify the challenges and required strategies to improve performance through packet-level interference management. We start by observing that, with the proposed technology, i.e., the IEEE 802.11p [5], the load on the wireless medium that results from periodic message exchange should carefully be controlled to prevent deterioration of the quality of reception of safety-related information. To this purpose, we propose a distributed transmission power control strategy called distributed fair power adjustment for vehicular environments (D-FPAV) that controls the beaconing load under a strict fairness criterion that has to be met for safety reasons. D-FPAV also allows a clear prioritization of event-driven over periodic messages. We then turn our attention to a fast and effective dissemination of event-driven emergency messages. We design a contention-based strategy called emergency message dissemination for vehicular environments (EMDV) that ensures a fast effective dissemination of alerts in a target geographical area in cooperation with D-FPAV. Finally, we evaluate the performance of the protocols in a highway traffic scenario with the use of a significantly extended version of the ns-2 [6] simulator that has been improved to account for the IEEE 802.11p draft and for more realistic propagation and interference patterns. Simulation results clearly show the following results: 1) D-FPAV can successfully control the beaconing load on the channel while ensuring that the probability of beacon reception is still high within the safety distance to the sending vehicle; 2) D-FPAV significantly increases the probability of one-hop reception of event-driven messages for all distances to the sender; and 3) when used in combination with D-FPAV, the EMDV protocol achieves a fast and effective dissemination of event-driven messages. The proposed suite of protocols provides a *comprehensive* solution for active-safety communications in IEEE 802.11-based vehicular networks.

The remainder of this paper is structured as follows. Section II identifies the communication challenges that exist in IEEE-802.11-based vehicular environments. Furthermore, it defines the goals that communication strategies for sending beacons and for sending emergency messages should accomplish. Section III presents recent studies most relevant to our work. Section IV formally defines the basis of our strategy to maintain the beaconing load under control, i.e., D-FPAV, which is also formally proven to achieve fairness among sending vehicles. In Section V, we propose the EMDV method to quickly and effectively disseminate emergency information within a geographical area. The simulator setup and configuration, as well as the modules that we developed to enhance the simulator, are given in Section VI. The performance evaluation of the proposed protocols is presented in Section VII. Finally, Section VIII summarizes the main results and presents an outlook on future work.

In this paper, great care has been taken to thoroughly analyze the challenges of power control as well as the proposed solution under realistic assumptions (in particular with respect to mobility, radio propagation, interferences, and protocol details of the IEEE 802.11p). At the same time, a formal and rigorous treatment of the challenges and of the proposed solutions is presented. However, a parameter-estimation problem occurs to bridge the gap between the rigorous treatment and the practical application for which we derive and evaluate an estimation procedure. We therefore start with the more formal treatment in Sections IV and V and move to a simulative assessment under realistic assumptions in Sections VI and VII. The results show that desired features can be maintained when moving from the formal treatment to realistic assumptions.

II. Identifying Challenges and Defining Goals

As outlined in the Introduction, safety applications can be enabled by two types of messages: 1) periodic and 2) event driven. Periodic status messages are intended to exchange state information from the sending vehicle, i.e., position, direction, speed, etc., and, possibly, aggregated information of the surroundings. Through this beaconing activity, safety applications acquire an accurate knowledge of the surroundings and can therefore detect potentially dangerous situations for the driver.

The key challenge related to this beaconing activity is to control the channel load to avoid channel congestion. This assessment is supported by the following facts. As defined by the U.S. Federal Communications Commission [7], we assume the existence of a single 10-MHz wide channel where only safety information is exchanged.[1] The data rates provided by the IEEE 802.11p [5] range from 3 to 27 Mb/s, where the lower ones will be preferred for safety applications due to their robustness against noise and interferences [8]. The channel access mechanism of IEEE 802.11 systems, i.e., the distributed coordination function (DCF), is an asynchronous approach that cannot efficiently utilize the wireless medium. According to previous studies [9], [10] and the Vehicle Safety Communications Project Final Report [11], it is envisioned that several messages per second from each vehicle will be needed to provide the required accuracy for safety applications. Furthermore, additional transmission repetitions could be considered to overcome the effects of packet losses due to collisions and fading. Finally, according to recent studies [12], safety-related messages will be relatively large, i.e., between 250 and 800 bytes, due to security-related overhead (e.g., digital signatures and certificates). A back-of-the-envelope calculation easily shows that (for example, with 100 neighboring nodes that send ten packets per second, each of size 500 bytes) the generated load can be much higher than the available bandwidth (3 Mb/s with the most robust modulation/coding scheme).

In a previous study [13], we evaluated the reception rates of periodic broadcast messages in a setup as previously described for different configurations of transmission power and packet-generation rate. On one hand, the results of our evaluation show that, as expected, increasing the generation rate of beacon messages decreases the probability of successful reception of each

[1] Such a channel has been coined a high-availability low-latency (HALL) channel.

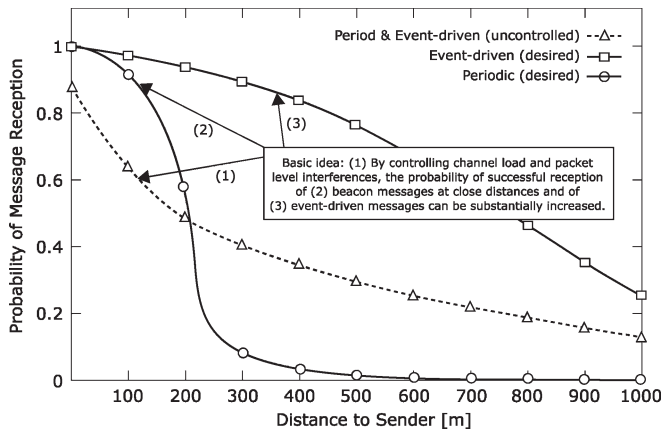


Fig. 1. Expected probability of successful reception of periodic and event-driven messages in case the communication behavior and the resulting channel load is uncontrolled. In comparison, the performance of periodic and event-driven messages is shown, as it should be achieved by active packet-level interference management.

of them. On the other hand, we have observed that, although increasing the transmission power extended the communication range to farther distances, it could also lead to a congested wireless medium where reception rates for vehicles close to the sending vehicle decreased due to packet collisions. Section VII presents the simulation results of configuring different transmission power values for beacon messages.

Accounting for these observations, we propose to fix the packet generation rate at the minimum required by safety applications and to adjust the transmission power of beacons in case of congestion. This mechanism should keep the load on the wireless medium below a certain level, called the maximum beaconing load (MBL). To illustrate our design goal, we schematically show in Fig. 1 the communication performance that can be achieved by applying packet-level interference management based on transmit power control to all periodic message transmission. Without control of the channel load, the probability of successful message reception will already significantly drop at close distances, and emergency messages will not experience a better reception performance than periodic messages. On the other hand, controlling and managing the interference introduced by periodic beacon messages, as illustrated in Fig. 1, the desired performance for active-safety-related communications can be achieved, i.e., periodic messages experience a high reception probability at close distances, and event-driven emergency messages achieve an enhanced performance. Consequently, we might need to accept lower reception probabilities for periodic messages at farther distances. Note that the transmit power control mechanism must be fully distributed and quickly react to the very dynamic topologies of vehicular networks. In addition, strict fairness must be guaranteed, because it is very important that every vehicle has a good estimation of the state of all vehicles (with no exception) in its close surroundings. More specifically, a higher transmit power should not be selected at the expense of preventing other vehicles from sending/receiving their required amount of safety information. In Section IV, we propose D-FPAV, which is a distributed strategy for adjusting the transmission power of periodic messages inspired by a max-min principle; the minimum of the transmission power of vehicles has to be maximized while confining the beaconing load below the MBL.

Contrary to beacons, event-driven messages follow a reactive strategy, i.e., they are issued when a hazard has been detected. Event-driven messages need to be quickly and effectively disseminated within the geographical area where the danger can be a threat. The main challenge for the information dissemination scheme is related to the fact that event-driven messages will share the wireless channel with periodic messages. Thus, in case of high vehicular traffic density, a high data load will be experienced on the channel, which, in turn, can result in longer channel access time and an increased number of packet collisions (see [13]). Furthermore, vehicular networks are a challenging environment with respect to radio-wave propagation due to a high number of reflecting mobile obstacles that can randomly degrade the strength of the received signal (see [14], where the analysis of empirical data is summarized).

In Section V, we propose EMDV, a strategy for disseminating emergency information within a geographical area with short delay. EMDV has been designed by taking into account probabilistic radio propagation characteristics and potentially high channel load. For safety reasons, information dissemination and beaconing to be "correctly" balanced. As a basis, a prioritized channel access mechanism, e.g., enhanced distributed channel access (EDCA) [15], as suggested in the IEEE 802.11p draft, should be used to reduce the channel access time for event-driven emergency messages. On top of that, we propose to use D-FPAV to adjust (through the MBL parameter) the amount of bandwidth available for unexpected emergency information, thereby increasing the probability of successful emergency message reception.

III. Related Work

Periodic one-hop broadcast communications are the basic mechanism for supporting safety applications, and their performance has been addressed in several vehicle-to-vehicle communication studies. In this context, Xu *et al.* [9] identify "infeasible regions" (situations) where potential safety applications requirements cannot be satisfied due to technological limitations. Their assessment is based on an evaluation of the performance of several layer-2 repetition strategies in terms of the number of updates per period of time and the probability of reception failure for different fractions of channel capacity assigned to this type of messages. In a previous work [16], we studied the probability of successful reception with respect to the distance from the transmitter of periodic IEEE 802.11 one-hop broadcast messages in vehicular scenarios. In addition, the effects of a probabilistic radio propagation model and the EDCA scheme suggested in IEEE 802.11p were shown. The results demonstrated that the CSMA/CA approach is highly challenged when coordinating broadcast transmissions in high vehicular traffic-density scenarios with probabilistic propagation phenomena. Furthermore, the study confirmed the beneficial effect of EDCA on channel access time for messages with higher priorities.

However, to the best of our knowledge, none of the existing approaches aims at controlling the load on the wireless channel where safety-related information exchange will take

place. Furthermore, congestion control strategies that were designed for nonvehicular environments do not address the specific challenges of vehicular networks due to their different goal, e.g., commonly focusing on unicast flows for end-to-end connections.

Existing power control studies in mobile networks frequently intend to maximize the overall system capacity, energy consumption, or connectivity for point-to-pint communications and, therefore, are not applicable to vehicular networks (see the work of Kawadia and Kumar [17] for a description of the design principles of power control in wireless ad hoc networks). The increasing interest caused by the potential of vehicle-to-vehicle communication has encouraged some researchers to adopt conventional power control or fairness approaches to vehicular environments. In this group, Artimy *et al.* [18] and Wischhof *et al.* [19] propose a power control scheme to maximize connectivity and a utility fair function to share the broadcast medium, respectively. Although the proposed strategies could perfectly be valid when focusing on nonsafety applications, they still fail to satisfy all the safety constraints outlined in Section II.

With respect to information dissemination, we can find several strategies in the field of vehicle-to-vehicle communication that take advantage of the existence of positioning systems, e.g., GPS, to improve simple flooding. These approaches are designed according to different criteria that correspond to different types of applications and environments.

On one hand, there is a group of studies that address nonsafety applications and, therefore, are not designed according to strong reliability constraints and provide little or no attention to a reduction of the delay experienced during the dissemination process. These schemes, e.g., [20]–[25], intend to deliver information over large distances, i.e., from several kilometers to complete cities. In addition, there are nonsafety information dissemination schemes that address smaller areas, e.g., to enable cooperative driving, such as [26].

On the other hand, several proposals exist, which consider time-critical safety applications, such as [27]–[30], which intend to deliver the information to all vehicles within local areas (up to a couple of kilometers) with low delay. Durresi *et al.* propose in [27] to construct a hierarchical structure among cars that drive in the same direction to efficiently manage the dissemination process. However, highly dynamic topologies would not be supported, e.g., with cars entering or leaving the road. Sormani *et al.* [28] suggest selecting message forwarders by the use of a probabilistic scheme, which is not proven to be a valid approach to reliably deliver time-critical information.

The authors of [29] and [30] propose interesting schemes to disseminate the emergency information in a certain direction by making use of contention periods, i.e., after a message transmission, all receivers wait for a certain time before forwarding the message. Briesmeister *et al.* [30] favor the retransmission of receivers located at farther distances from the sender by the selection of shorter waiting times. Biswas *et al.* [29] select random waiting times and utilize an implicit acknowledgment scheme to cancel retransmissions from nodes closer to the danger (where the message originated).

Our proposal for information dissemination described in Section V makes use of the two latter principles (from [29] and [30]) and further complements them with mechanisms that were aimed at reducing dissemination delay and improving reliability, particularly in high channel load conditions.

Furthermore, contrary to the aforementioned studies, we consider probabilistic radio propagation on a per-packet basis for the evaluation of our protocols. Although recent channel characteristic studies such as [31]–[36] have shown that the wireless channel for intervehicle communication at 5.9 GHz is subject to frequency- and time-selective fading, we assume that these effects can be taken care of by the IEEE 802.11p. For instance, the experienced Doppler spreads up to 2 kHz, and the root-mean-square (RMS) delay spreads around 0.8 μs, due to multipath radio propagation are handled by an increased guard interval of 1.6 μs between successive OFDM symbols and an intercarrier spacing of 156.25 kHz [32], [33]. Without these adoptions, which are part of the drafted IEEE 802.11p Standard, the communication would be vulnerable to intercarrier interference and intersymbol interference. We are also aware that multipath propagation and high vehicular mobility cause a variation of the channel condition over time, by which, depending on the used symbol rate and the size of a packet, channel estimations that were performed at the beginning of a transmission may become invalid at the end of the packet. Although this problem is explicitly not covered by the current IEEE 802.11p draft, various proposals on how one can overcome this impairment exist. The approach in [32], for instance, suggests using an advanced receiver in which time-domain channel estimation and frequency-domain channel tracking is performed to equalize the channel. According to the authors, this proposal has already been implemented, is completely IEEE 802.11p compliant, and was evaluated in more than 300 field trials. One different solution from Zhang *et al.* applies differential modulation, such as differential phase-shift keying, to mitigate the frequency-selective channel fading [37].

IV. Fair Congestion Control

In this section, we present the D-FPAV algorithm, which makes use of transmit power control to achieve the following design goals.

1) *Congestion control*. Limit the load on the medium produced by periodic beacon exchange.
2) *Fairness*. Maximize the minimum transmit power value over all transmission power levels assigned to nodes that form the vehicular network under Constraint 1.
3) *Prioritization*. Give event-driven emergency messages higher priority compared to the priority of periodic beacons.

As explained in the following discussion, the congestion control requirement (Constraint 1) is applied only to beacon messages, which is coherent with our design goal of controlling the channel bandwidth assigned to periodic safety-related messages. Note that, when event-driven messages also contend for the channel, this condition might be violated at some nodes, which is perfectly fine, because in our proposed framework, the entire channel bandwidth will be used in case a situation of immediate peril is detected. With regard to Constraint 3,

we anticipate that prioritization is achieved through the EDCA mechanism available in the IEEE 802.11p and by always sending an event-driven emergency message using the maximum possible transmit power.

In the following discussion, we first present some definitions and a description of the network model. Second, we introduce the formal definition of the beaconing problem and the designed algorithm to solve the problem, assuming ideal conditions. Last, we address the estimation approaches required to implement a feasible solution for realistic environments. The resulting tradeoffs and the corresponding performance evaluation are presented in Section VII-B.

Assume that a set of nodes $N = \{u_1, \ldots, u_n\}$ moves along a road modeled as a line[2] of unit length, i.e., $R = [0, 1]$. Each of the network nodes periodically sends a beacon with a predefined beaconing frequency F by using a certain transmit power $p \in [P_{\min}, P_{\max}]$, where $P_{\min}(P_{\max})$ denotes the minimum (maximum) transmit power.

Definition 1—PA: Given a set of nodes $N = \{u_1, \ldots, u_n\}$, power assignment (PA) is a function that assigns to every network node u_i, with $i = 1, \ldots, n$, a value $\mathrm{PA}(i) \in (0, 1]$. The power used by node u_i to send the beacon is $\mathrm{PA}(i) \cdot P_{\max}$.

Definition 2—CS Range: Given a PA and any node $u_i \in N$, the carrier-sense (CS) range of u_i under the PA, denoted $\mathrm{CS}(\mathrm{PA}, i)$, is defined as the intersection between the commonly known CS range[3] of node u_i at power $\mathrm{PA}(i) \cdot P_{max}$ and the deployment region R. The CS range of node u_i at maximum power is denoted $\mathrm{CS}_{MAX}(i)$.

Given a PA, the network load generated by the beaconing activity under the PA is defined as follows.

Definition 3—Beaconing Load Under PA: Given a set of nodes N and a PA for the nodes in N, the beaconing network load at node u_i under the PA is defined as

$$BL(\mathrm{PA}, i) = |\{u_j \in N, j \neq i : u_i \in \mathrm{CS}(\mathrm{PA}, j)\}|$$

where $\mathrm{CS}(\mathrm{PA}, j)$ is the CS range of node u_j under the PA.

Informally speaking, the beaconing load is measured in terms of the number of nodes that contain node u_i in their CS range. In fact, under the assumptions that the beaconing frequency is fixed to the same value for all the nodes and that beacon messages have the same size, the observed channel load is a function of the number of nodes in the surroundings. Note that the aforementioned definition of beaconing load can easily be extended to account for different beaconing frequencies in the network and for beacon messages of different sizes.

Formally speaking, the goal of D-FPAV is to solve the following problem in a fully distributed environment.

Definition 4—Beaconing Max-Min Tx Power Problem (BMMTxP): Given a set of nodes $N = \{u_1, \ldots, u_n\}$ in $R = [0, 1]$ and a value for the MBL, determine a PA, i.e., $\overline{\mathrm{PA}}$, such that the minimum of the transmit power used by nodes for beaconing is maximized and the network load experienced at the nodes remains below the beaconing threshold, i.e., MBL. Formally

$$\begin{cases} \max_{\mathrm{PA} \in \mathbf{PA}} \left(\min_{u_i \in N} \mathrm{PA}(i)\right) \\ \text{subject to} \\ \quad BL(\mathrm{PA}, i) \leq \mathrm{MBL}\ \forall i \in \{1, \ldots, n\} \end{cases}$$

where $\mathbf{PA}$ is the set of all possible PAs.

Note that solving BMMTxP addresses design goals 1 and 2 at the beginning of this section, where the MBL is used to control the congestion generated by the beaconing activity. As the simulation results in Section VII will show, design goal 3 can be achieved by transmitting beacons that use the transmit power computed by D-FPAV and by transmitting event-driven emergency messages at full power.

The proposed D-FPAV algorithm is based on the FPAV algorithm [38], a centralized algorithm for solving BMMTxP that assumes *global* knowledge (node positions). FPAV itself is based on a "water-filling" approach [39]. Node power levels are iteratively increased by the same amount $\epsilon \cdot P_{\max}$, starting from the minimum level, and this process is continued as long as the condition on the MBL is satisfied. When the process stops, all nodes have increased up to the same power level. Notice that, in a previous work [38], we proposed a "second stage" of the FPAV algorithm to achieve per-node maximality. At the second stage, specific nodes could further increase their transmission power until no node can increase without violating the condition on beaconing load, which is in accordance with the formal definition of the max-min fair allocation as in [39]. However, simulation experiments where global knowledge was assumed showed that the second stage could only achieve a marginal gain in scenarios with high network dynamics [38]. Because of this case and due to the higher complexity, by which implementing per-node maximality would add to the distributed protocol, the second stage of the algorithm is not considered here.

D-FPAV is based on the following factors: 1) executing the FPAV algorithm at each node with the information gathered from received beacons; 2) exchanging the locally computed transmit power control values among surrounding vehicles; and 3) selecting the minimum power level among the one locally computed and those computed by the surrounding vehicles. The D-FPAV algorithm is summarized in Fig. 2. A node u_i continuously collects information about the status (e.g., current position, velocity, and direction) of all the nodes within its CS_{MAX} range. These nodes are the only ones that node u_i can affect when sending its beacon. The communication range[4] is typically smaller than the CS range; thus, a strategy based on multihop information propagation is needed to obtain the information from nodes outside the communication range. Various alternatives for implementing this strategy will be discussed later in this section. Based on the status of all nodes within CS_{MAX} range, node u_i makes use of FPAV to compute

[2]Modeling the road as a line is a reasonable simplification in our case, because we assume the communication ranges of the nodes to be much larger than the width of the road.

[3]The CS range, in ideal conditions, is the distance to which a node's transmissions can be sensed and therefore prevents other nodes from accessing the channel at this time.

[4]Communication range is defined in this paper as the distance where the received signal power of a transmitted message matches, on average, the minimum power specified to successfully receive a message.

Algorithm D-FPAV: (algorithm for node u_i)
INPUT: geographical positions of all nodes in $CS_{MAX}(i)$
OUTPUT: a power setting $PA(i)$ for node u_i, such that the resulting power assignment is an optimal solution to BMMTxP

1. Based on the geographical positions of all nodes in $CS_{MAX}(i)$, use FPAV to compute the maximum common transmit power level P_i s.t. the MBL threshold is not violated at any node in $CS_{MAX}(i)$
2a. Disseminate P_i to all nodes in $CS_{MAX}(i)$
2b. Collect the power level values computed by nodes u_j such that $u_i \in CS_{MAX}(j)$ and store the received values in P_j
3. Assign the final power level: $PA(i) = \min\left\{P_i, \min_{j:u_i \in CS_{MAX}(j)}\{P_j\}\right\}$

Fig. 2. D-FPAV algorithm. Note that, to disseminate/collect information to/from nodes outside the communication range, multihop communication is involved (steps 1, 2a, and 2b).

the maximum common value P_i of the transmit power for all nodes in $\mathrm{CS}_{MAX}(i)$ such that the condition on the MBL is not violated (Step 1). Note that this computation is based only on local information (i.e., the status of all the nodes in $\mathrm{CS}_{MAX}(i)$), and it might globally be infeasible (i.e., it might violate the condition on the MBL at some node). To account for this case, node u_i delivers the computed common power level P_i to all nodes in $\mathrm{CS}_{MAX}(i)$ (see Step 2a). Meanwhile, node u_i collects the same information from the nodes u_j such that $u_i \in \mathrm{CS}_{MAX}(j)$ (see Step 2b). Knowing the power levels computed by the nodes in its vicinity, node u_i can assign the final transmit power level, which is set to the minimum among the value P_i computed by the node itself and the values computed by nodes in the vicinity (see Step 3). Setting the final power level to the minimum possible level is necessary to guarantee the feasibility of the computed PA.

In the Appendix, we formally prove that, under quite idealized conditions, D-FPAV solves the BMMTxP problem within one round of communication, i.e., the time between two successive broadcast transmissions that contain a node's local power computation and that it has polynomial time complexity. Later in this section and, more extensively, in Section VII, we will show that, even in practical scenarios where these conditions are not met and where the time interval between two broadcast transmissions that contain a node's local power computation is increased, D-FPAV still performs very well.

Note that, although a perfect information accuracy from *all* nodes inside $\mathrm{CS}_{MAX}(i)$ is required to *guarantee* strict fairness, achieving such a perfect knowledge is very difficult in a fully distributed fast-moving scenario as given by vehicular ad hoc networks. Furthermore, the geometric concept of a CS *range* might even not apply in reality. Although the formal treatment remains valid, even with generalized definitions of CS_{MAX}, the actual problem then is to estimate which nodes can be considered to be "in" CS_{MAX}. Hence, D-FPAV is expected to operate in situations in which nodes have incomplete knowledge about the environment (the status of nodes within CS_{MAX}). Under these conditions, D-FPAV is not guaranteed to provide strict fairness. However, as shown in the simulation results in Section VII, D-FPAV is very effective in achieving a very close approximation to fair power control, even if the knowledge of the environment is inaccurate.

Another facet of the problem of estimating which nodes are in CS_{MAX} is given by a tradeoff between information accuracy and additional overhead on the channel. Clearly, the only option for acquiring the status information from nodes located outside the communication range is to make use of a multihop strategy, i.e., nodes retransmit the status of their neighbors. To determine this strategy, the following design decisions have to be made: 1) how often the neighbors' status should be forwarded; 2) what range of neighbors must be included; and 3) which transmission power must be used to transmit this information. We propose to put together the P_i values with the status information of the corresponding nodes inside the $\mathrm{CS}(i)$ range[5] and then to improve efficiency to piggyback this aggregated information in beacon messages ("extended beacons").

Now, decisions have to be made on how often the aggregated information should be piggybacked in the beacons and which transmit power should be used to send extended beacons. In making these choices, the tradeoff exists between additional overhead on the channel and the accuracy of the neighbor's status information available at the nodes. To select the better option, we evaluate three different configurations in Section VII: 1) Piggyback the aggregated status information to each beacon; 2) piggyback the aggregated status information to every fifth beacon; or 3) piggyback the aggregated status information to every tenth beacon and transmit it with power $\mathrm{PA}(i)$ (the transmit power value as computed by D-FPAV). We considered that sending piggybacked beacons with a lower frequency than one every ten beacons would cause D-FPAV to deal with information that is very outdated.

Finally, the issue of how fast D-FPAV reacts to changes in the vehicle density (and, hence, of the offered channel load) is of interest. From a theoretical viewpoint, we prove in the Appendix that D-FPAV computes an optimal solution to BMMTxP within the time of two successive periodic beacon transmissions, i.e., the time of two successive broadcast transmissions that contain a node's local power computation. This result holds under the assumption that the offered channel load does not change during this time, which might not be the case in a practical scenario. Similar to the case of imperfect knowledge of the number of nodes within CS_{MAX}, suboptimal transmit power allocations will be expected in the presence of changing load conditions, which leads to some performance degradation with respect to optimal idealized conditions. However, the extensive simulation results in this paper and in [41] show that, also in practical scenarios, D-FPAV achieves a quite accurate and stable control of the beaconing load, which indicates that the rate of change in traffic load conditions is expected to be lower than the frequency of information update used, supporting the computation of the PA.

[5]Unlike in our previous work [40], the choice of $\mathrm{CS}(i)$ instead of $\mathrm{CS}_{MAX}(i)$ has been adopted to achieve a lower overhead in areas with high load on the channel. Although a smaller amount of potential surrounding vehicles can be discovered, a lower overhead benefits the performance of the beaconing activity, as shown in the results in Section VII.

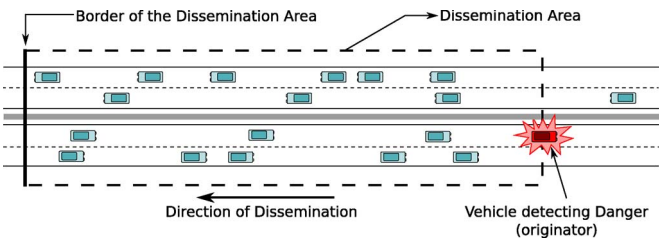


Fig. 3. Relevant area for dissemination of emergency information after an accident detection in a highway. Cars in the opposite direction are included in the dissemination area, because they can support the information dissemination process.

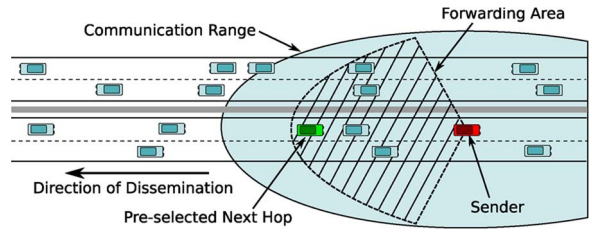


Fig. 4. Sender perspective when utilizing the EMDV protocol.

V. Dissemination of Emergency Information

The second main goal in Section II is the dissemination of event-driven emergency information within a geographical area. To deliver a message[6] that contains information about an existing threat, an effective strategy that offers short delay is required.

We assume that a vehicle that detects a hazard issues an event-driven emergency message to warn the drivers that approach the danger. The originating node, according to the corresponding safety application, specifies the relevant area for dissemination of the alert (*dissemination area*). The alert must be distributed in the complete area, i.e., up to the border of the dissemination area (see Fig. 3), possibly via multihop transmissions, with high reliability and short delay. In this paper, we study the case where roads do not comprise any intersection (or highway entry/exit) and make the reasonable assumption that the communication range of an emergency message is larger than the road's width. (The protocol proposed in this paper can be extended to disseminate the emergency message in two opposite directions and to support road junctions, e.g., with smart strategies such as those proposed in [42] or with the use of digital maps, which is left to our future work.)

The main purpose of our dissemination strategy is to select the appropriate nodes to efficiently forward the message in the direction of dissemination to cover the entire dissemination area. The proposed strategy needs to overcome the different challenges that exist in a vehicular environment, such as dealing with uncertainties that result from node mobility, fading phenomena, and packet collisions. Furthermore, the wireless channel is also utilized for periodic beacon exchange; thus, a relatively busy medium can be encountered by event-driven emergency messages in dense vehicular traffic situations.

In previous studies [43], [44], we showed the satisfactory performance of a forwarding strategy based on the use of the geographical positions of the nodes combined with a contention-based approach. According to this strategy and to overcome the uncertainties on the aforementioned message reception, an event-driven message is transmitted in a broadcast fashion, and all vehicles that receive it are potential forwarders. To decide which node actually forwards the message, a contention period is started: To favor the speed of the process, each receiving node makes use of GNSS data to select a timeout value inversely proportional to the progressed distance in the direction of dissemination with respect to the actual sender. The node(s) whose timeout fires first will rebroadcast the packet. Nodes that still wait for their timeout to fire and that receive a rebroadcasted packet will cancel their rebroadcast attempts. The advantages of using a contention-based approach for forwarding is that, compared to unicast-based forwarding, the probability that at least one node forwards the message is significantly increased. There is a chance for redundant (duplicate) rebroadcast, however, and when appropriately controlled, these duplicates increase robustness.

Motivated by the idealistic environments assumed to design existing forwarding strategies and by the findings in [13] and [44], we propose the emergency message dissemination for vehicular environments (EMDV) strategy for the dissemination of safety critical information. EMDV is based on the following three design principles.

1) A contention scheme is used after the broadcast transmission of the message to deal with uncertainties in terms of reception failure caused by node mobility, fading phenomena, and collisions.
2) To minimize the delay, the contention strategy is complemented with the selection of one specific forwarder made at transmission time, referred to as the next hop. This step is possible due to the status information acquired from safety beacons. The specific forwarder, in case of correct reception, immediately forwards the message.
3) The reliability of the dissemination process is increased by the following factors: 1) assuming a forwarding range shorter than the communication range and 2) a controlled message retransmission scheme within the dissemination area.

Fig. 4 shows a sketch of a sender perspective, which must preselect a next hop among known nodes and then broadcast the message. The forwarding area, which is limited by the forwarding range, identifies the area where potential next forwarders can be located, i.e., both the preselected next hop and the group of nodes that will start the contention period upon the reception of the message. A forwarding range shorter than the communication range is selected to improve the efficiency of the process. In our previous study [44], we showed how undesired message duplicates could be reduced in contention-based approaches by a limitation of the "contention" range, i.e., the forwarding range in our case. These message duplicates are the result of poor reception rates of broadcast messages at distances close to the communication range, as we have experienced in our vehicular scenarios (see Section VII-A).

[6]Unless otherwise stated, in this section, by "message" we mean "event-driven emergency message."

```
Procedure: PrepareMessage( )
    if countMessages < maxMessages then
      nextHop ← FindNextHop( )
      TransmitEMDVMessage( nextHop )
      countMessages ++
      PrepareContention( sent )

Procedure: FindNextHop( )
    nextHop ← broadcastAddress
    if borderDisseminationArea ∈ myForwardingArea then
      return nextHop
    progress ← 0
    for each neighbor ∈ myNeighborTable do
      if neighborPosition ∈ myForwardingArea and
         neighborProgress > progress
      then
         progress ← neighborProgress
         nextHop ← neighborAddress
    return nextHop

Procedure: ReceiveMessage( )
    if myPosition ∈ disseminationArea then
      if senderPosition ∈ myForwardingArea or
         borderDisseminationArea
                ∈ myForwardingArea ∩ senderForwardingArea
      then
         countMessages ++
      if countMessages ≥ maxMessages then
         CancelContention( )
      else if messageDestinationAddress = myAddress then
         if contending then
           CancelContention( )
         PrepareMessage( )
      else if myPosition ∈ senderForwardingArea and
         not contending
      then
         PrepareContention( received )

Procedure: PrepareContention( flag )
    if flag = sent then
      time ← maxContentionTime + maxChannelAccessTime
    else time ← maxContentionTime×(1−myProgress/forwardingRange)
    contending ← true
    Contend( time )
```

Fig. 5. EMDV protocol for emergency message dissemination.

EMDV is composed of four main procedures, as shown by the pseudocode description of the protocol in Fig. 5. A node that transmits an emergency message invokes the *PrepareMessage()* procedure. This procedure first checks whether the message has already been transmitted for the maximum number of times (*maxMessages*) within the node's forwarding area. If not, the *FindNextHop()* procedure is invoked to determine the message's destination node. Note that this address is used only to (possibly) select a specific forwarder and speed up message propagation, but the message sent to the channel still has the broadcast address specified at the link layer. This method ensures that every node that receives an emergency message passes it to the upper layers and that no acknowledgment is issued for a received message. Once the message has been transmitted, the message counter is increased, and a contention period is started to verify that at least one neighbor forwards the message. The *FindNextHop()* procedure essentially scans the neighbor table of the sender to find (if any) the neighbor in the sender's forwarding area with the highest progress in the direction of dissemination. If no neighbor in the dissemination direction can be found or if the sender's forwarding area is at the border of the dissemination area (see Fig. 3), no specific forwarder is selected, and *NextHop* is set to *broadcastAddress*.

The *ReceiveMessage()* procedure is invoked when a node receives an emergency message and first ensures that the node lies inside the dissemination area to proceed. Then, it is checked whether the received message has been sent by a node that is farther in the direction of dissemination and lies inside its own *forwardingArea*. In this case, the message can be considered to be a sort of "implicit ack" of message forwarding, and the corresponding message counter is increased so that contention for forwarding the message can be canceled if enough "implicit acks" have already been received. If the aforementioned conditions are not satisfied and the receiving node is located inside the *forwardingArea* of the sender, the dissemination criteria are used to determine whether immediate or contended forwarding will be performed: If the receiving node is indicated as the intended forwarder in the *NextHop* field, then the message is forwarded with no contention by invoking the *PrepareMessage()* procedure; otherwise, a contention period is started by invoking the *PrepareContention()* procedure. Note that a contention will be canceled if enough implicit acks have been received. For this requirement to work, independent of the underlying vehicle traffic density, i.e., in both low- and high-density scenarios, a node will increment the corresponding message counter for its own (re)transmission and for each (re)transmission sent by a node inside its own *forwardingArea*. Therefore, the contention will be canceled if enough (re)transmissions sent from within its own *forwardingArea* have been received or if the message has been repeated often enough by the node itself, e.g. when there is no possible forwarder who can relay the message. Furthermore, if the load due to periodic beaconing is controlled and limited, the number of sufficient implicit acks is basically a matter of desired reliability and independent of the actual vehicle traffic density.

Finally, the protocol has to be adjusted with respect to two specific situations. First, the contention period after delivering the message to lower layers (*PrepareMessage()*) must take into account the time that the message needs to access the channel and transmission. To account for this case, the contention time is set to $maxContentionTime + maxChannelAccessTime$ when $flag = sent$. Second, nodes located within *forwardingRange* from the border of the *disseminationArea* will act a little differently, because the message must not travel farther distances than *borderDisseminationArea*. Therefore, the following cases hold: 1) They will not select a *nextHop*; instead, the *broadcastAddress* will be utilized, and 2) they will increment *countMessages* when receiving a message from any node that is also located within *forwardingRange* of *borderDisseminationArea* instead of only counting the ones that come from their *forwardingArea*.

In this paper, we study the performance of the protocol in challenging saturation conditions. However, EMDV can easily be adapted to also perform well in sparse network situations. For instance, the case in which no vehicle is known in the direction of dissemination can easily be addressed either by storing the emergency message and issuing it when a beacon from a new vehicle is received or by repeating the EMDV contention until a predefined lifetime timer expires.

VI. Simulation Modeling and Setup

In the next section, we will evaluate the performance of the two proposed protocols, i.e., D-FPAV and EMDV, with the use of the network simulator ns-2.28. We first describe the simulation setup, including the scenario utilized, and the configuration of our proposed strategies. Special emphasis is devoted to the extension modules implemented into the ns-2 simulator with more accurate propagation and interference models, realistic vehicular movement patterns, and adjustments to model the current IEEE 802.11p specifications.

A. Network Simulator

The utilization of appropriate models and their correct configuration is a critical aspect in the evaluation of wireless communications. Furthermore (and as pointed out in existing studies, e.g., [45]), although ns-2 [6] is a widely used network simulator, it shows (in its standard release) insufficient accuracy in the lower layers of its wireless modules. Thus, we have modified and extended many models of the standard distribution of ns-2.28 to provide our simulations with a higher level of fidelity with respect to reality and, moreover, to model the current development status of vehicle-to-vehicle communications technology. In the following discussion, we briefly describe the main enhancements.

First, the interference and reception model has been extended with cumulative noise capabilities. The original ns-2.28 code does not keep track of all ongoing messages at a node's interface, i.e., it does not accumulate the power level of all ongoing interferences. As other network simulators already do, e.g., GloMoSim [46], we accumulate the power of all interfering signals together with the existing background noise (*Noise*) to determine whether the reception of a message is successful. Moreover, we modified the capture feature, because the standard distribution of ns-2.28 only allows a message to be captured if it arrives when the channel is idle. According to the current wireless chipsets' capabilities [47], our implementation also allows the successful reception of a message that arrives during a busy period of the channel, as long as the following inequality is satisfied during the complete reception time:[7]

$$P_r \geq I + CpTh \tag{1}$$

where P_r is the power of the received message, I corresponds to the cumulative power level of all existing interferences plus *Noise*, $CpTh$ is the capture threshold, and all powers are expressed in decibels. To have a higher level of accuracy, we consider all signals that arrive at the interface with a power higher than *Noise* instead of discarding signals below CSTh as in the original ns-2.28. The finite-state machine implemented to model cumulative noise has been validated by setting up a table of all possible combinations of triggers and conditions for each state, eliminating nonfeasible combinations and determining the finite-state machine's transactions to the remaining ones. These modifications have recently been merged into the official ns-2 tree and are publicly available as part of the ns-2.33 release; thus, see either [48] or [49] for further details.

[7]According to private conversations with the electronics company Siemens within the NoW Project [4], a packet cannot correctly be received if it arrives between 4 and 10 μs after the previous one due to resynchronization issues.

TABLE I
ns-2.28 MAC and PHY Configuration Values for Simulations of Vehicle-to-Vehicle Communications

Parameter	Value
Frequency	5.9 GHz
Data rate	3 Mbps
RxTh	-94 dBm
CpTh	5 dB
CSTh	-96 dBm
Noise	-99 dBm
Antenna gain	0 dB
Antenna height	1.5 m
Slot time	16 μs
SIFS time	32 μs
Preamble length	32 μs
PLCP header length	8 μs

With respect to the medium access control (MAC) layer, we thoroughly analyzed and bug fixed the ad hoc channel access mechanism (see [50]) according to the IEEE 802.11 standard [51] (which is inherited by the IEEE 802.11p). With respect to the physical (PHY) layer, ns-2.28 models a Lucent WaveLAN 802.11 direct-sequence-spread-spectrum radio interface. To model a wireless access in vehicular environments OFDM system, which operates at 5.9 GHz with 10-MHz channels, several modifications were required according to the IEEE 802.11a [52] Standard and the IEEE 802.11p [5] draft. Independent of the data rate used to transmit a message payload, the preamble and the physical-layer convergence protocol (PLCP) header are always transmitted using the lowest data rate, i.e., 3 Mb/s. The modulation scheme that provides 3 Mb/s is the most robust one, i.e., binary phase-shift keying (BPSK) with the lowest coding rate (1/2). However, note that 16 service bits of the PLCP header are transmitted with the payload data rate instead of the basic rate and that padding and tail bits are added to fill up the last symbol of a message. In addition, the slot-time parameter is adapted to support larger communication distances. Again, see [48] and [49] for a detailed report on the implementation issues. Table I presents the main parameters that were configured in our version of the simulator for a data rate of 3 Mb/s, which was used to illustrate the performance evaluation of the proposed protocols.

In addition, a more appropriate radio propagation model than the ones implemented in ns-2.28 has been used. Among many radio models in the literature, the probabilistic Nakagami distribution [53] is utilized and suggested by many authors as a suitable model for estimating the physical fading phenomena of mobile communication channels due to the good match with empirical data collected from mobile communications experiments, such as in [54]–[56]. Recently, Taliwal *et al.* and Yin *et al.* have performed real-world tests on highways, and they suggest the use of the Nakagami fading model for these types of vehicular scenarios [14], [57]. Furthermore, Taliwal *et al.* implemented the model into ns-2.28, which we use in this study. The Nakagami-m model derives the received signal strength from a multipath environment where the different signal components randomly arrive because of

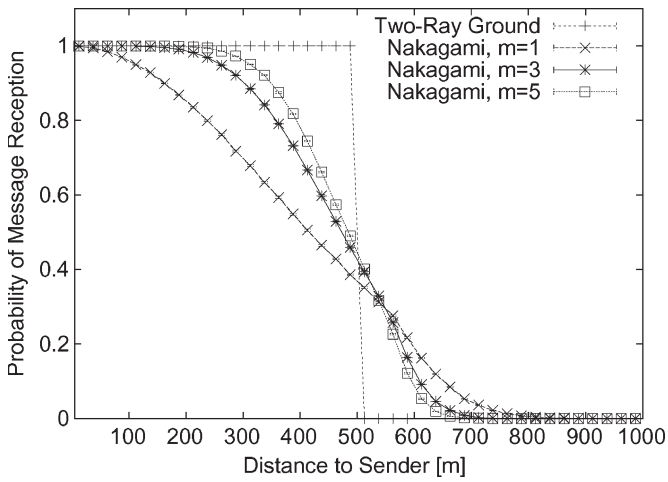


Fig. 6. Probability of successful beacon reception (no interference from other transmissions) with respect to the distance when no fading (two-ray ground) and Nakagami-m fading with different intensities ($m = 1, 3, 5$) is considered. The transmit power has been set to the power required to achieve a communication range of 500 m when considering the two-ray ground model.

the different propagation phenomena. It is used to estimate the signal amplitude at a given distance from the transmitter as a function of two parameters Ω and m. The following expression describes the Nakagami probability density function of the received signal amplitude x:

$$f_{amp}(x; m, \Omega) = \frac{2m^m}{\Gamma(m)\Omega^m} x^{2m-1} \exp\left(-\frac{m}{\Omega}x^2\right), \qquad m \geq \frac{1}{2} \tag{2}$$

where Ω defines the average received power at a specific distance and is set to match the two-ray ground path loss of ns-2.28 in our simulations. The m value identifies the fading intensity, which depends on the environment, and Γ is the *Gamma function*. As illustrated in Fig. 6, the probability of successful message reception is perfect up to the intended communication range if no fading is considered. With fading, the probability of successful message reception is already less than 100% within the intended communication range. Moreover, the probability of reception decreases if the fading intensity is increased. For instance, a Nakagami $m = 1$ distribution is equivalent to a Rayleigh distribution and models a rough non-line-of-sight scenario, whereas for parameters $m > 1$, Nakagami models an increased line-of-sight scenario. To demonstrate that our proposals are valid over a wide range of fading intensities, we have configured values of $m \in \{1, 3, 5\}$ in this paper. In our evaluation, we refer to Nakagami $m = 1$ as *severe* fading conditions, to Nakagami $m = 3$ as *medium* fading conditions, and to Nakagami $m = 5$ as *low* fading conditions. In addition, as mentioned in Section III, we assume that OFDM receivers can mitigate the challenges that are imposed by the time and frequency selectivity of the wireless channel and therefore assume that varying received signal strengths during the reception of a single packet can be equalized.

Last, microscopic movement patterns validated with measurements of real-world German highway traffic, which were provided by DaimlerChrysler for the Fleetnet [58] and NoW [4] Projects, were utilized (see [59]). The evaluated vehicular scenarios consist of a 6-km-long bidirectional highway with three lanes per direction. Unless otherwise stated, we utilize a vehicular density that corresponds to an average of 11 vehicles per kilometer in each lane, which travels at an average speed of more than 120 km/h. Note that this scenario corresponds to free-flow vehicular traffic, i.e., the vehicular density can be much higher on many real highways for several hours during the day. However, we are interested in high-speed scenarios with high dynamics, where the utilization of high transmission power and packet generation rates is envisioned.

B. Simulation Setup

In the simulated highway scenarios, all vehicles are equipped with wireless communication interfaces and generate ten beacons per second, which is the packet generation rate required by many safety applications according to existing studies, e.g., [9] or [10]. The size of each packet is configured to 500 bytes as the mean value suggested in security studies, e.g., [12], due to the security-related overhead (i.e., digital signature plus a certificate). The maximum communication range for beacons is configured to 1000 m according to the IEEE 802.11p Standard, which states that vehicular communications will occur over distances of up to 1000 m between *high-speed* vehicles.

The data rate utilized is 3 Mb/s due to the robustness of the BPSK modulation scheme (see [8]): It requires the lowest signal-to-interference plus noise ratio (SINR) to successfully receive a message, i.e., 5 dB. In addition, the IEEE 802.11 contention window is configured to 15 slots in our simulations. Larger contention window values caused average channel access times higher than 100 ms, i.e., not all generated beacons could be transmitted to the channel.

When evaluating D-FPAV, a reference node or originator generates single-hop event-driven messages, i.e., one per second. When evaluating EMDV, the event-driven message is destined to a dissemination area with a segment of the highway starting at the originator and going up to 2 km opposite the driving direction. The originator is located around 4 km of our highway segment, and accordingly, the 2-km-long dissemination area is located in the middle of the 6-km scenario. All event-driven messages, independent of whether D-FPAV is used, are sent with a CR $= 1000$ m. Moreover, event-driven messages are configured with a higher link-layer priority than beacons that use the differentiated access categories (EDCA mechanism), as described in the IEEE 802.11e [15].

With respect to the communication strategies, we set the MBL of D-FPAV to two different values, i.e., 2.5 and 2 Mb/s, to evaluate the prioritization of event-driven messages over beacons. Note that, here, we express the MBL threshold in terms of megabits per second instead of the number of nodes within the CS range, as done in Section IV. However, the two measures are equivalent when the packet generation rate and the packet size (assumed to be the same for all the nodes) are known. We fix each neighbor entry in the neighbor table to 15 bytes (corresponding to vehicle identifier and position) and specify that nodes delete neighbor entries from their neighbor table that are older than 1 s. Finally, each node will estimate

TABLE II
CONFIGURATION PARAMETERS FOR D-FPAV AND EMDV EVALUATION

PARAMETER	VALUE
Number of lanes	3 × direction
Vehicle density	11 cars/km per lane
Average speed	121.86 km/h
Propagation model	Nakagami $m \in \{1, 3, 5\}$
802.11p data rate	3 Mbps
Contention window	15
Packet size	500 Bytes
Communication range:	
Event-driven messages	1000 m /19 dBm
Beacons (without D-FPAV)	1000 m /19 dBm
Beacon generation rate	10 packets/s
D-FPAV	On, Off
D-FPAV *MBL*	2.5 Mbps, 2.0 Mbps
Neighbor entry size	15 Bytes
Dissemination area length	2 km
EMDV *forwardingRange*	300 m, 500 m, 700 m
EMDV *maxMessages*	1, 2, 3
EMDV *maxContentionTime*	100 ms
EMDV *maxChannelAccessTime*	10 ms

its CS range for the local execution of the D-FPAV algorithm. The CS range is given by the distance at which the average path loss causes the signal strength to drop below the CS threshold, i.e., the one computed using the two-ray ground model of ns-2.28. Note that the estimated CS range is only used to calculate the expected load in the network under a specific PA and to determine the neighbors that will be included in extended beacons. The propagation of a transmitted signal will still follow the Nakagami-m fading model.

With respect to EMDV, we fix the *maxContentionTime* to 100 ms and the *maxChannelAccessTime* to 10 ms as appropriate values for our scenario according to a study of one-hop broadcast communications, which is outlined at the beginning of Section VII-A. The forwarding range is configured to three different values, i.e., 300, 500, and 700 m, to study the tradeoff between reliability, overhead, and delay. Last, we study the performance of three different values for the amount of retransmissions (*maxMessages*) in a node's *forwardingArea*, i.e., 1, 2, and 3.

To obtain statistical significance, we simulate ten different highway scenarios, with the same average vehicle density, with ten random seeds for every selected configuration. Each simulation consists of 11 s of simulated time, and the statistics that correspond to the first second of simulation are not taken into account as a transitory state. All results that were obtained are represented with a 95% confidence interval.

The configuration details are summarized in Table II.

VII. PERFORMANCE EVALUATION

A. IEEE 802.11p One-Hop Broadcast Communication

As aforementioned, our simulation scenario consists of a bidirectional highway where all vehicles are equipped with wireless communication systems and periodically transmit ten packets per second (beacons). Before evaluating the D-FPAV and EMDV protocols, we study some aspects of the IEEE-802.11p-based one-hop broadcast communications in vehicular scenarios. The purpose of this evaluation is to obtain valuable insights into the performance of vehicular networks, to corroborate the performance statements of Section II, and to determine appropriate values for the configuration of our protocols.

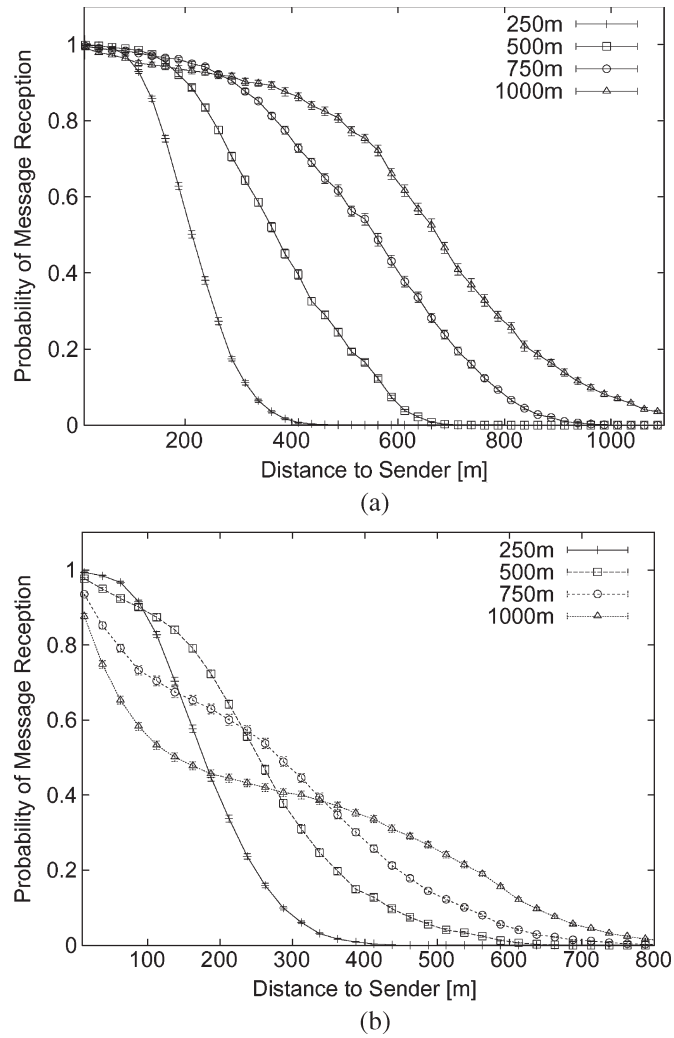


Fig. 7. Probability of successful beacon reception with respect to the distance to the sender for different communication ranges, i.e., different transmit powers. In (b), the tradeoff between using higher transmit powers to reach further distances and provide more reliable communication at close distances by using lower transmit powers is clearly shown. (a) Highway scenario with 36 vehicles/km. (b) Highway scenario with 66 vehicles/km.

Fig. 7 compares the probability of successful beacon reception with respect to the distance between the sender and the receiver for various values of CR (from 250 to 1000 m) and two different vehicular densities. Fig. 7(a) presents the results obtained with the lower vehicular density, i.e., 36 cars/km, and Fig. 7(b) presents the results obtained with the higher one, i.e., 66 cars/km. In both scenarios, we considered medium channel-fading conditions.

In general, increasing the transmission power of one message increases its robustness against power fluctuations and interference; thus, it can reach farther distances.[8] However, increasing the transmission power of all nodes in a network increases their CS ranges and, therefore, the number of nodes that share the channel at all locations.

[8]Note that an analysis of message reception failures and a comparison between deterministic and probabilistic models is out of the scope of this paper. See our previous work [60] for a detailed study.

We can observe that, although the channel is not saturated, i.e., when the amount of simultaneous transmissions from neighboring nodes is negligible, increasing the transmission power does not significantly decrease the reception rates at close distances and provides improved reception rates at farther ones. In fact, no drawback due to using higher transmission power values can be observed in Fig. 7(a), where the lower vehicular density is utilized.

On the other hand, CR $= 750$ m in Fig. 7(b) experiences a significantly higher number of collisions at close distances from the sender due to the higher level of interfering signals. Moreover, the reception rates at close distances from the sender are further reduced in the case of CR $= 1000$ m. The reason for these low reception rates at close distances from the sender is the inability of the channel access mechanism to coordinate the high number of neighboring nodes in this scenario.

We remark that, due to the kinetic energy of moving vehicles, reception rates at close distances are more relevant from a safety perspective. In the case of the higher vehicular density and with a packet generation rate of ten packets per second, a CR of, e.g., 500 m, would be a better choice than 1000 m, although a higher CR provides an increased probability of reception at far distances. Therefore, the lack of node transmit power control can result in a lower safety level due to the decreased reception rates experienced at close distances from the transmitters.

Further analysis on different parameter configurations in this setup assisted us in adjusting the designed protocols, as well as the modulation and contention window value of the channel access strategy, which are depicted in Table II.

B. D-FPAV Performance

To evaluate D-FPAV performance, we consider two main simulation setups: 1) D-FPAV On and 2) D-FPAV Off. In the D-FPAV Off simulations, all beacons are sent at maximum power (CR $= 1000$ m), because no power control is applied. On the other hand, in the D-FPAV On simulations, beacons are sent using the transmit power as computed by D-FPAV. In this set of simulations, we fix the MBL to 2.5 Mb/s. To study the performance in different fading environments, we have configured Nakagami-m to reflect severe-, medium-, and low-fading conditions. However, we will focus on the results obtained in medium-channel-fading conditions and complement them with a selected set of observations obtained in severe- or low-fading environments.

The main metrics considered to evaluate D-FPAV's performance are given as follows: 1) the probability of successful reception of a beacon message with respect to the distance and 2) the average channel access time (CAT). The CAT is computed for all nodes in the highway, and it is used to corroborate the claim that D-FPAV uniformly reduces the load on the channel in the network, i.e., it achieves fairness. The probability of reception is used to assess D-FPAV's effectiveness and the appropriate prioritization of safety-related messages (the design goals in Section II), which is obtained by ensuring a high probability of correctly receiving beacons at close distances from the sender and, at the same time, by increasing the probability of successful reception of event-driven messages at all distances.

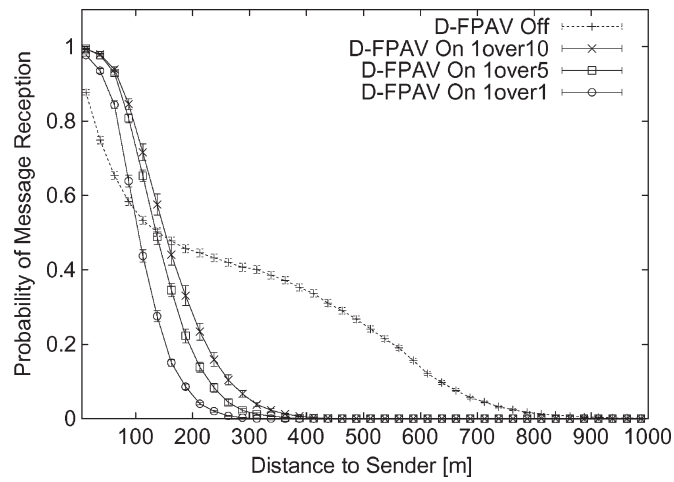


Fig. 8. Probability of successful beacon reception with respect to the distance to the sender for different D-FPAV configurations, i.e., information exchange at low, medium, and high frequency. The wireless channel has been configured to reflect medium-channel fading conditions.

Before performing the aforementioned experiments, we have to fix the estimation procedure with respect to obtaining information on which the node is residing in the "CS range." As indicated in Section VI-B, each node will estimate its CS range as the distance given by the average path loss experienced in our simulations, i.e., the one computed using the two-ray ground model of ns-2.28. We evaluate different strategies that D-FPAV can use to obtain the status information from vehicles that are driven inside a node's CS range, as described in Section IV. Fig. 8 presents the probability of successful reception of beacons for the different strategies and with D-FPAV Off for comparison. These strategies are differentiated by the generation rate of extended beacon messages that contain not only the status information of the transmitter but the positional information about its surrounding nodes as well.

Fig. 8 shows the results obtained with D-FPAV Off and D-FPAV On using the different configurations of the protocol. Reception rates with D-FPAV Off present low values due to the high load that exists on the wireless medium and the resulting packet collisions. Indeed, the high saturation on the wireless medium causes reception rates below 60% for nodes located at a distance of 100 m or farther. Note that the near-far effect[9] of radio-wave propagation allows higher reception rates at very close distances from the transmitter, i.e., 90% at a few meters, and causes the strong decrease up to 150 m. By adjusting the transmission power of all beacons, including the extended ones, the desired results are achieved (see Fig. 8): An increased probability of reception at close distances from the sender for the cases where each beacon is an extended one (denoted 1over1), where every fifth beacon is sent as an extended beacon (denoted 1over5), and every tenth beacon is sent as an extended beacon (denoted 1over10).

Comparing the three curves in Fig. 8, we can see how sending a lower number of extended beacons achieves higher reception rates. Note the existing tradeoff between information accuracy

[9]The near–far effect refers to the significantly higher received power of messages sent from close distances compared with messages sent from further ones due to the strong decrease in radio wave power along the distance.

and the associated overhead of D-FPAV. Sending a higher number of extended beacons offers the possibility of obtaining more up-to-date information about the status information from surrounding nodes (farther than direct communication distances). However, the larger number of extended beacons causes a higher amount of offered load to the channel and consequently requires a further reduction of the transmission power to adhere to the MBL constraint. Note that extended beacons are significantly larger than nonextended ones. In the case of 1over10, the introduced D-FPAV overhead, due to an average extended beacon size of 1120.6 bytes, is already 12.4%. This extended size corresponds to an average of 41.37 known neighbors within the resulting CS range (448 m in this case; $\mathrm{CR} = 356$ m).

Therefore, we conclude that sending one extended beacon every ten transmissions presents the best tradeoff between accuracy and overhead among the studied options. Note that, due to the high number of nodes within the communication range of each other, the same information is repeated by several nodes. Thus, extending one beacon every ten provides a sufficient degree of neighbor table accuracy at a lower price than 1over5 in terms of overhead. Thus, in the following discussion, we adopt the 1over10 strategy in the D-FPAV design.

The observations are also valid if we consider more or less severe fading of the wireless channel. As illustrated in Fig. 9(a), the probability of successful message reception increases at close distances and decreases at far distances if D-FPAV is not used and fading is severe. Due to the greater variation of the received signal strengths, which causes a reduced number of interferences from far distances, the chance to successfully decode a message is increased for close distances. At the same time, the probability is decreased for far distances. Severe fading can, therefore, also be shown as a natural way of performing congestion control. The same phenomenon does not occur if D-FPAV is enabled, as shown in Fig. 9(b). The interference level is already controlled and limited by the D-FPAV algorithm; thus, the probability of successful message reception decreases over all distances if the fading intensity increases. Nevertheless, comparing the curves in Fig. 9(a) and (b), the benefit of transmission power control also clearly exists in severe fading environments.

Fig. 10(a) and (b) present the probability of successful packet reception with respect to the distance of beacons and single-hop event-driven messages with D-FPAV On and Off under severe- and medium-fading channel conditions. As aforementioned, not using power adjustment results in a high load experienced on the channel, which, in turn, causes a high number of packet collisions and low reception rates. Note that, if beacons and event-driven messages are sent with the same transmission power (D-FPAV Off), event-driven messages achieve higher reception rates at closer distances. As explained in a previous work [16], a prioritized channel access category decreases the probability of experiencing collisions with neighboring nodes.

Using the D-FPAV mechanism and setting the MBL parameter to 2.5 Mb/s results in an average reduction of the beacon's transmission power from 19 dBm to 4.9 dBm, which decreases the communication range from 1000 m to an average of 356 m. Therefore, the CS range is reduced to 448 m, which, according

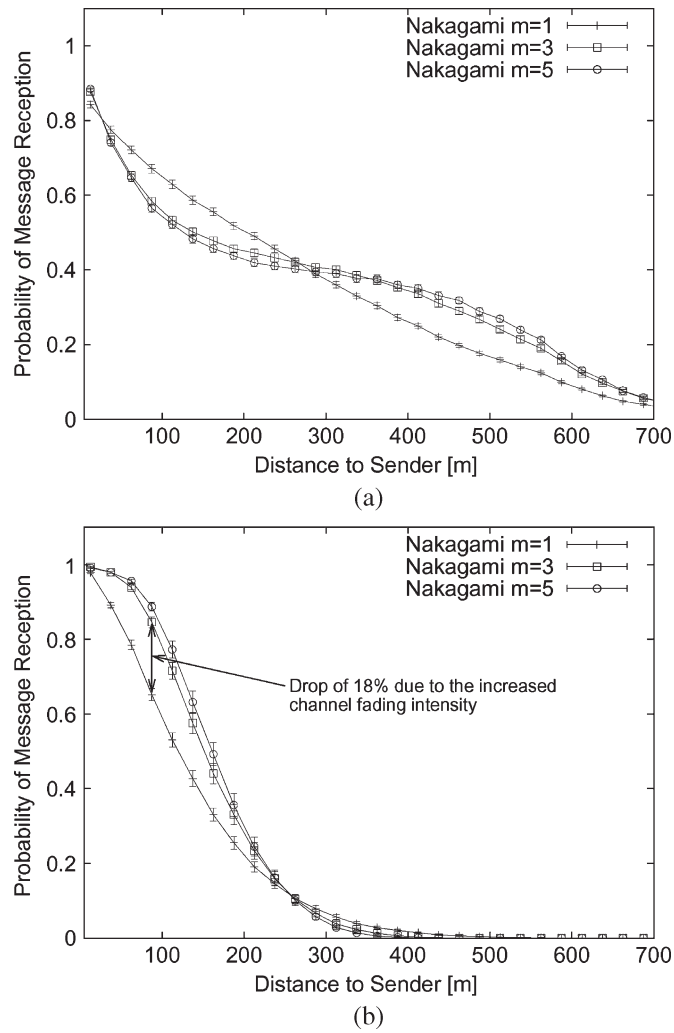


Fig. 9. Probability of successful beacon reception with respect to the distance for D-FPAV On/Off and different fading intensities of the Nakagami-m distribution. (a) D-FPAV Off. (b) D-FPAV On 1over10.

to an average of 66 cars/km, corresponds to an average of 59.13 vehicles within the CS. Note that 59.13 vehicles correspond to an offered load of 2.36 Mb/s, which is less than the MBL threshold (2.5 Mb/s) due to the conservative approach of D-FPAV, i.e., the minimum of the PA values received from nodes within CS_{MAX} is selected (see Section IV).

To evaluate the saturation on the channel, we also computed the average channel busy time ratio. As intended, the reduction of the transmission power decreases the average-channel busy-time ratio experienced by all nodes in the highway from about 86.2% with D-FPAV Off to 62.2% with D-FPAV On, i.e., a 24% decrease.

The resulting power adjustment allows D-FPAV to fulfill its design goal of ensuring high message reception rates at close distances from the sender, which corresponds to the safety distance of a vehicle.[10] As outlined in Section II, achieving a

[10]The safety distance of a vehicle commonly refers to the distance that a driver needs to stop the vehicle completely, and it is approximately calculated (in meters) as half of the value of the speed (in kilometers per hour). For example, a car that is drive at 120 km/h has a safety distance of approximately 60 m.

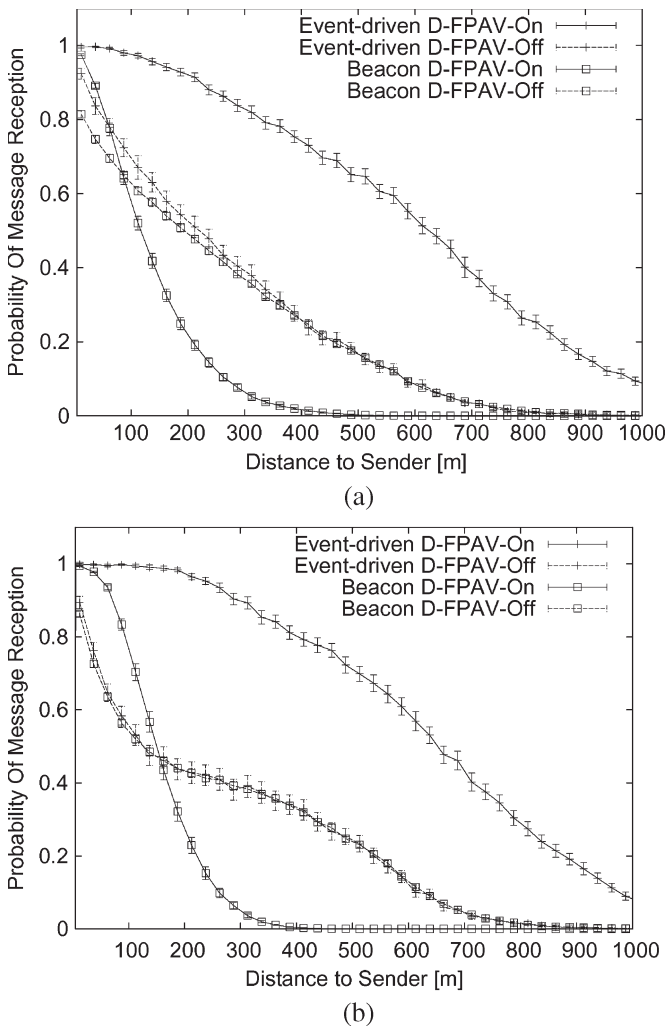


Fig. 10. Probability of successful reception of beacons and one-hop event-driven messages (without retransmission) with respect to the distance to the transmitter, with D-FPAV On/Off and MBL $= 2.5$ Mb/s. (a) Severe fading with Nakagami $m = 1$. (b) Medium fading with Nakagami $m = 3$.

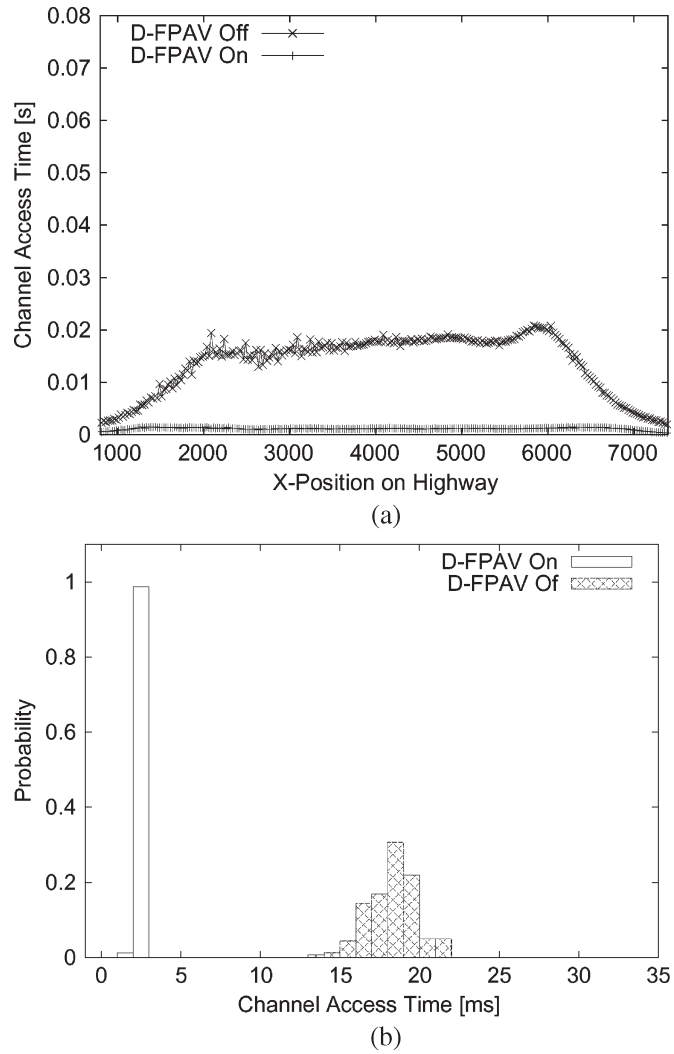


Fig. 11. Average channel access time experienced by beacons with and without D-FPAV and an MBL $= 2.5$ Mb/s. (a) Average channel access time experienced by each node with respect to its position on the highway. (b) Probability of experiencing a channel access time.

good estimation of the close environment is critical to identify dangerous situations. In our scenario with a medium fading intensity [see Fig. 10(b)], the beacons' probability of successful reception presents higher values up to distances of 160 m with D-FPAV On, e.g., an increase of 41.7% at 100 m (from 54.0% with D-FPAV Off to 76.5% with D-FPAV On). In addition, we can observe a significant increase in the reception rates experienced by each transmission of an event-driven message at all distances with D-FPAV On. Experiencing a lower load on the medium allows event-driven messages, which are not restricted in terms of transmission power, to achieve improved reception rates not only at close distances (e.g., a 78.6% increase at 100 m from 55.7% to 99.6%) but also at further ones (e.g., 192.2% increase at 500 m from 24.3% to 71.0%). The price to pay for these improvements is the lower reception rates of beacons for distances farther than 160 m, which, however, are distances where the information conveyed by beacons is less relevant compared with the "closer beacons" and emergency messages. In an environment with higher fading intensity [see Fig. 10(a)], the difference between D-FPAV On and Off is, as expected, slightly reduced for beacon messages. However, the probability of reception of emergency messages still significantly benefits from the load reduction of D-FPAV.

To evaluate the fairness of the algorithm, we study the average channel access time of all nodes on the highway. Fig. 11(a) illustrates the results obtained with medium-fading conditions, where each vehicle is represented with its middle position[11] during the simulation run. In this case, the results of only one scenario are presented such that we will not average out different vehicular densities in different segments of our highway. We omit a detailed presentation of CAT results in severe- and low-fading channel conditions, because the difference from the medium-fading condition is only marginal.

We can observe how the average channel access time has been reduced from 17.5 ms to 1.1 ms when using D-FPAV. Furthermore, if no power control is applied, nodes can experience considerably different values of CAT, which range from about 13 ms to 22 ms [see Fig. 11(b)]. The CAT reflects the amount of load on the channel at that particular location; thus,

[11] We compute the middle position of a vehicle as the middle point between its position at the beginning of the simulation and its position at the end.

the results obtained with D-FPAV Off show that different nodes have different opportunities of sending and correctly receiving messages, impairing fairness. On the other hand, when D-FPAV is active, all the nodes experience similar CAT values, which range between 0.9 and 1.3 ms. Therefore, similar opportunities of sending and correctly receiving safety messages are experienced by the nodes in the network. In other words, D-FPAV achieves its design goal, i.e., fairness.

C. EMDV Performance

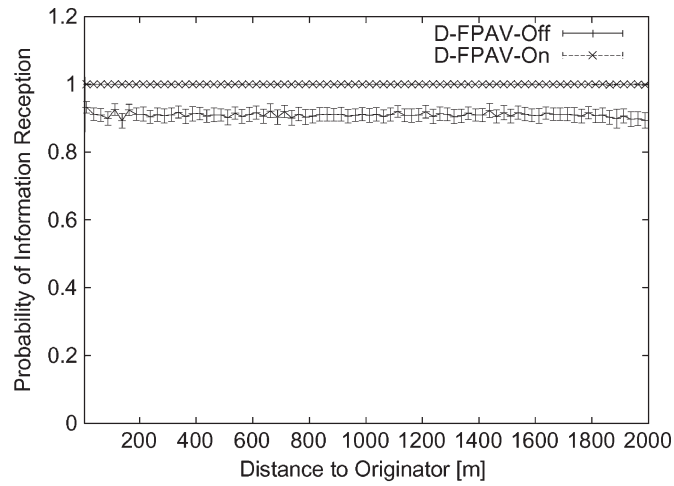
Let us now evaluate the performance of the EMDV protocol when operating with D-FPAV Off and in synergy with the D-FPAV protocol. We recall that, in the investigated scenario, the reference node generates an emergency message that has to be delivered within the relevant area for dissemination. In our case, the dissemination area is 2 km long and lies in the middle of our highway segment. In addition, three different values of the *maxMessages* parameter are studied (1, 2, and 3), as well as three values of the *forwardingRange* (300, 500, and 700 m). Unless otherwise stated, the utilized *forwardingRange* will be the middle value, i.e., 500 m. Again, we will focus on the result obtained with medium-channel-fading conditions and subsequently complement them with the results from severe- and low-fading conditions.

Fig. 12(a) presents the probability that the emergency information is successfully received by vehicles located inside the dissemination area when $maxMessages = 1$. With D-FPAV Off, we observe a reception rate of 90.9% averaged over the dissemination area. The use of the D-FPAV protocol increases the emergency information reception rates up to an average of 99.9%. The result shows the dependency of the success of the dissemination strategy on the channel load conditions.

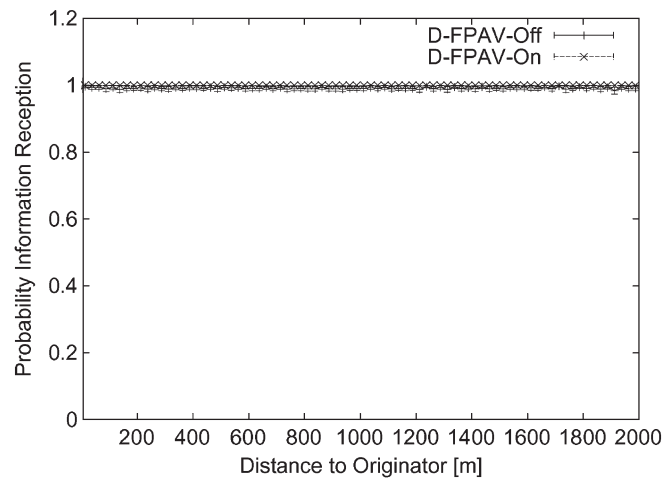
Fig. 12(b) shows the probability of reception in the dissemination area obtained when setting $maxMessages = 2$. Note how the curve that presents the reception rates obtained with D-FPAV Off is increased with respect to the values in Fig. 12(a) when $maxMessages = 1$, i.e., from 90.9% to a 99.1% on average. To achieve a 100% probability of reception within the dissemination area with D-FPAV Off, *maxMessages* must be set to three repetitions [see Table III(b)]. In fact, we discovered that, due to the high load on the channel, several dissemination processes did not succeed at all, because the initial transmission of the originator was not received by at least one of the intended receivers. As intended, allowing more message repetitions within a node's *forwardingRange* enhances the reliability of the protocol and resolves that problem, but at the cost of an increased overhead.

In Table III(b), we also present the average number of retransmissions caused by the EMDV protocol, i.e., the number of times that the emergency message is transmitted by any node within the dissemination area. Observe how, with D-FPAV Off and Nakagami $m = 3$, increasing *maxMessages* from 1 to 2 causes the emergency message to increase from 39.5 to 67.1 retransmissions per dissemination process and to 87.6 in the case of allowing three repetitions.

When using D-FPAV, the most efficient EMDV choice is to configure $maxMessages = 1$, because it already reaches



(a)



(b)

Fig. 12. Probability of information delivery inside the dissemination area with respect to the distance from the message originator (with multihop retransmissions) with D-FPAV On/Off and MBL = 2.5 Mb/s. (a) $maxMessages = 1$. (b) $maxMessages = 2$.

TABLE III
AVERAGES OF THE PROBABILITY OF RECEPTION AND THE AMOUNT OF RETRANSMISSIONS EXPERIENCED WITHIN THE DISSEMINATION AREA WITH A $forwardingRange = 500$ m AND FOR THREE VALUES OF *maxMessages*, 1, 2, AND 3. (a) AVERAGES FOR SEVERE FADING WITH NAKAGAMI $m = 1$. (b) AVERAGES FOR MEDIUM FADING WITH $m = 3$. (c) AVERAGES FOR LOW FADING WITH $m = 5$

(a)

maxMessages	**1**		**2**		**3**	
D-FPAV	**Off**	**On**	**Off**	**On**	**Off**	**On**
Prob. reception	98.4%	99.9%	100%	100%	100%	100%
Retransmissions	45.6	14.6	75.8	22.3	101.8	30.0

(b)

maxMessages	**1**		**2**		**3**	
D-FPAV	**Off**	**On**	**Off**	**On**	**Off**	**On**
Prob. reception	90.9%	99.9%	99.1%	100%	100%	100%
Retransmissions	39.5	16.2	67.1	24.3	87.6	32.5

(c)

maxMessages	**1**		**2**		**3**	
D-FPAV	**Off**	**On**	**Off**	**On**	**Off**	**On**
Prob. reception	89.6%	99.9%	99.2%	100%	100%	100%
Retransmissions	39.4	16.6	67.1	24.5	87.0	33.7

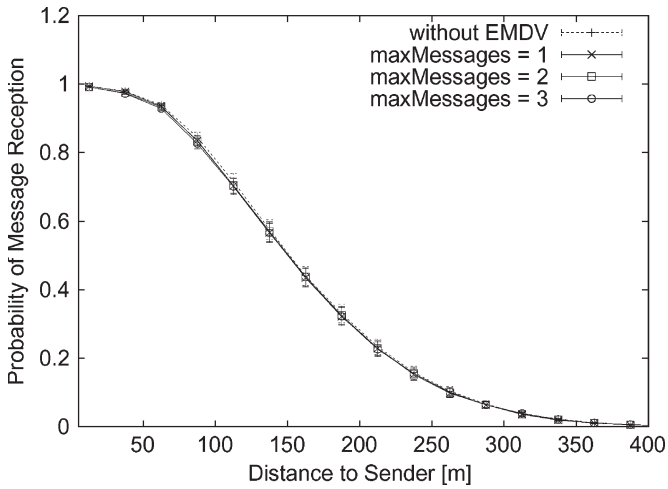


Fig. 13. Probability of successful reception of beacons with respect to the distance, with D-FPAV On and MBL $= 2.5$ Mb/s and while disseminating emergency information for three values of *maxMessages*, i.e., 1, 2 and 3.

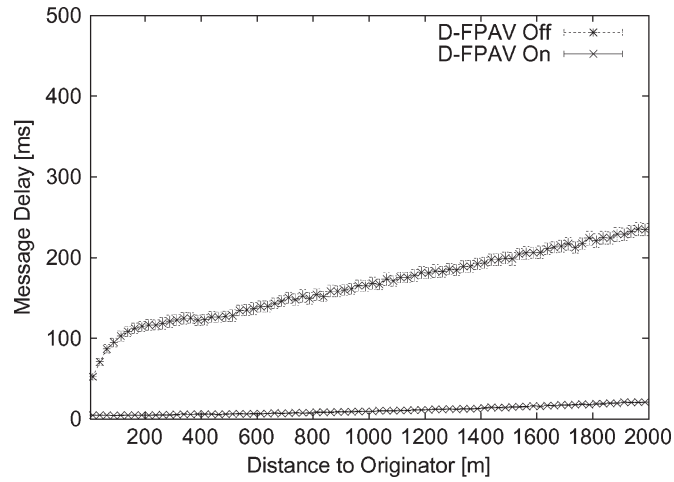


Fig. 14. Reception delay of the emergency information inside the dissemination area with respect to the distance from the message originator (with multihop retransmissions) with D-FPAV On/Off, and MBL $= 2.5$ Mb/s.

a 99.9% delivery rate while requiring fewer messages, on average, than the other choices, i.e., 8.1 and 16.3 messages fewer than configuring *maxMessages* to 2 and 3, respectively. However, it is the responsibility of the application designer to define the requirements for communication protocols, i.e., *maxMessages* 3 may be preferred due to the 100% reception rates achieved with both D-FPAV On and Off.

If we consider different fading intensities, we observe that a low-fading intensity, i.e., Nakagami $m = 5$, presents equivalent results to Nakagami $m = 3$ in terms of probability of reception and the number of retransmissions [see Table III(c)]. On the contrary, in more severe-fading environments such as Nakagami $m = 1$, the dissemination reliability for D-FPAV Off and $maxMessages = 1$ is higher compared with the medium-fading condition. Here, the interference level and the chance of a packet to collide is decreased, resulting in an improved dissemination process and, thus, in a higher probability of reception within the dissemination area. However, due to the higher fading and the lower probability of successfully receiving a message at farther distances, the number of retransmissions is slightly increased.

Furthermore, we analyzed the effect that event-driven messages have on beacon reception rates during the complete simulation. Fig. 13 presents the probability of successful reception of beacons sent by the reference node for the three values of *maxMessages* and for the case where no EMDV process is started, always with D-FPAV On. The difference between the three curves stays below 2% for all distances, showing the low impact that the emergency dissemination process has on the reception rates of periodic messages. In fact, a simple calculation of the additional load required by each dissemination process shows that, with the configured emergency message size of 500 bytes and a retransmission count between 15 and 30 [see Table III], in each dissemination process, only up to 15 Kbytes of data will be sent in total. Because the total amount of data is transmitted within about 20 ms and taking into account some degree of spatial reuse (due to the large dissemination area), a "peak bandwidth utilization" of 375 Kbytes/s can be expected for the dissemination process.

In the following discussion, we focus on the performance of $maxMessages = 1$, which provides a 99.9% of delivery ratio with D-FPAV On and utilizes the least amount of overhead. Fig. 14 shows the average delay experienced by the nodes in the dissemination area[12] until receiving the emergency information with respect to the distance to the originator. Both curves present higher values for increasing distances, as expected due to the multihop dissemination approach. In the case of D-FPAV Off, event-driven messages are disseminated up to 2 km, with an average delay below 250 ms. This delay should be compared to the estimated driver reaction time, which is on the order of 700 ms and higher [61]. Furthermore, in case D-FPAV is utilized, the delay experienced significantly falls, i.e., from 52.3 ms to 4.7 ms for close distances to the sender and from 235 ms to 20 ms in the case of a vehicle located 2 km away from the originator. With respect to different fading intensities, we observed different delays only for the D-FPAV Off case, i.e., for $m = 1$, the average delay went up to 290 ms, and for $m = 5$, it went down to 226 ms. The delays when using D-FPAV On only slightly changed by 1 ms.

Another relevant parameter for safety is the *maximum* delay experienced by the information that will be delivered. To account for this instance, we measured the maximum time of all simulated scenarios that a node located at 2 km of the originator, i.e., at the other edge of the relevant area, has to wait until receiving the emergency information. According to the results obtained, the maximum delay experienced in the case of D-FPAV Off is 924 ms, whereas in the case of D-FPAV On, it is only 80 ms. Note the difference of 844 ms between both cases, which is a significant value compared with the aforementioned driver reaction time. Finally, we study the performance results obtained with a *forwardingRange* of 300 and 700 m [see Table IV]. Let us first focus on the values obtained with D-FPAV Off, where the channel load is not controlled. We can observe how the reception rates vary between 91% and 93% in all cases. With respect to the delay and amount

[12]Only the set of vehicles that receive the emergency message can be taken into account.

TABLE IV
AVERAGES OF THE PROBABILITY OF RECEPTION, THE AVERAGE DELAY, AND THE AMOUNT OF RETRANSMISSIONS EXPERIENCED WITHIN THE DISSEMINATION AREA FOR THREE VALUES OF THE *forwardingRange*: 300, 500, AND 700 m

forwardingRange	300 m		500 m		700 m	
D-FPAV	**Off**	**On**	**Off**	**On**	**Off**	**On**
Prob. reception	91.9%	99.9%	90.9%	99.9%	92.7%	99.8%
Avg. delay at 2 km	313 ms	27 ms	235 ms	20 ms	238 ms	17 ms
Retransmissions	47.2	11.6	39.5	16.2	37.1	13.2

of retransmissions, configuring a *forwardingRange* of 300 m presents the worst results due to the limitation of the number of possible forwarding nodes and a highly saturated wireless environment. The cases of 500 and 700 m do not present significant differences due to the low message reception probability between both distances, as illustrated in Fig. 10(b) ("Event-driven D-FPAV Off"). When D-FPAV is active, on the other hand, the three values of *forwardingRange* achieve almost a perfect message reception within the dissemination area. In a controlled wireless channel, as expected, allowing a larger *forwardingRange* allows for reaching the 2-km distance with fewer hops, thus presenting a shorter average delay, i.e., from 27 ms in case of a 300-m *forwardingRange* to 17 ms in case of 700 m. Furthermore, we can observe a higher robustness of the shortest *forwardingRange* (300 m), which presents the smallest number of retransmissions. Forcing shorter wireless hops decreases the probability of generating message duplicates due to the high probability of message reception up to the 300-m distance when the load is under control (see the "Event-driven D-FPAV On" curve in Fig. 10). The price to pay, as aforementioned, is a slower dissemination speed.

D. Choice of MBL Value

Finally, we evaluated the prioritization effect that a different choice of the MBL value has on both types of messages and, therefore, on the performance of our protocols. We simulated the same scenario as in the previous section, with an MBL set to 2 Mb/s, and describe the results that were obtained as follows. A smaller MBL value further restricts the transmission power utilized for beacons, i.e., it achieves a more strict prioritization of event-driven messages over periodic messages.

In the case of configuring MBL $= 2.0$ Mb/s (instead of 2.5 b/s), the average transmission range of beacons is decreased to 346 m (instead of 356 m) and the channel busy time ratio to 54.4% (instead of 62.2%). Fig. 15 presents the effect of configuring the MBL with the two selected values on the reception rates of single-hop messages. We can observe how, with MBL $= 2.0$ Mb/s, event-driven messages benefit from a lower load on the medium, which increases their probability of being successfully received over the distance. Note how this difference is more noticeable at far distances, i.e., from 500 m, due to the lower number of collisions that result from hidden terminals.[13]

With a lower MBL, the EMDV protocol achieves a more efficient performance due to the lower channel load and the

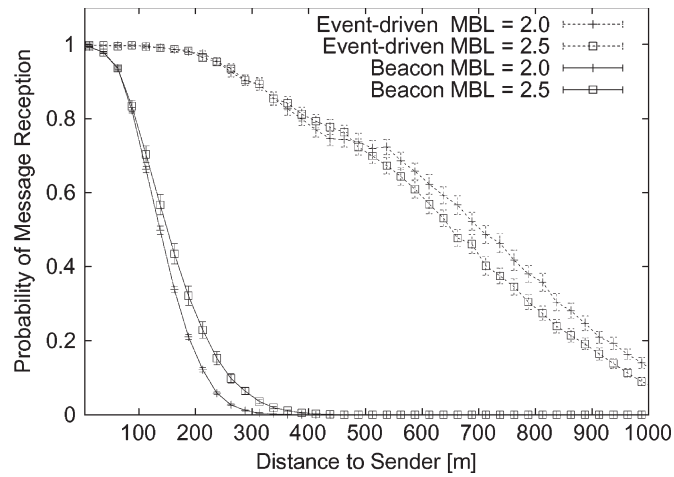


Fig. 15. Probability of successful reception with respect to the distance of beacons and one-hop event-driven messages (without retransmission) with D-FPAV On for MBL $= 2.0$ Mb/s and MBL $= 2.5$ Mb/s.

increased event-driven messages' reception rates. The probability of information reception with $maxMessages = 1$ and $forwardingRange = 500$ m obtains 99.9% along the dissemination area, which is similar to MBL $= 2.5$ Mb/s. However, a lower load on the channel results in a smaller channel access time for event-driven messages in every hop, which results in an average delay of 8 ms to deliver the emergency information at 2 km from the information originator, which is less than half the time compared with an MBL $= 2.5$ Mb/s. Furthermore, the number of messages sent per dissemination process is also lower with MBL $= 2.0$ Mb/s, i.e., 15.4 instead of 16.2.

VIII. SUMMARY AND CONCLUSION

This paper has been based on the assumption that vehicular networks will use the IEEE 802.11p or an 802.11 variant and that market penetration will be high. active-safety communication will consist of two types of messages: 1) periodic beacon messages and 2) event-driven emergence messages. We have shown that channel saturation can "easily" occur due to the load caused by beacon message transmissions. Simply increasing the rate or power will just make the channel conditions worse. In these "uncontrolled" saturated channel conditions, both types of messages might not be received where they are needed and, thus, will not contribute to the original goal of improving road traffic safety.

To satisfy the requirements of active-safety communication in vehicular networks also under these "stressed" conditions, we have proposed two communication strategies that can separately be used but show synergistic effects when combined. On one hand, we have proposed the D-FPAV algorithm to limit the beaconing load on the channel below a predefined

[13]In [60], we showed that the impact of hidden nodes in a broadcast environment increases with the distance to the transmitter. This effect occurs due to the capability of wireless interfaces to successfully receive a signal in the presence of an interference if the latter one is weak enough, i.e., the capture feature.

threshold while ensuring a high probability of beacon reception at close distances from the sender. On the other hand, we have proposed the EMDV protocol to disseminate emergency information within a geographical area.

D-FPAV is a transmit power control approach based on a strict fairness criterion that can maximize the minimum value over all transmission power levels assigned to nodes that form the vehicular network under a given constraint on the MBL. As a distributed algorithm, with D-FPAV, each node V needs as input the number of nodes that can sense node V's transmission. When this information is available, it can be proven that D-FPAV provides an optimal PA. Under realistic assumptions, the required input has to be estimated. We have shown, through a simulative investigation, that the estimation procedure is sufficiently accurate and with low communication overhead. The simulation results show that D-FPAV works very well in realistic vehicular environments.

The EMDV approach provides for robust and effective information dissemination of emergency information. For EMDV, we made use of the idea of contention-based forwarding that can very well deal with the unreliability of the channel and with node mobility. For the reduction of the dissemination delay, we also made use of beacon information and of classical position-based forwarding techniques in combination with the contention-based approach.

Synergy is gained when using both protocols together, because D-FPAV can ensure that the channel load, in particular the channel busy time, is kept at a level where EMDV (or other dissemination protocols) can successfully operate.

The performance of the proposed protocols has been analyzed via simulation. For a proper evaluation, we extended the network simulator ns-2 with more accurate reception, interference, and propagation models and adjusted it to the current version of the IEEE 802.11p draft. Furthermore, realistic vehicular movement patterns that correspond to fast-moving German highway scenarios were utilized.

According to the results obtained, our suite of protocols presents a viable solution for improving active-safety-related communications in IEEE 802.11-based vehicular networks. When we consider the two proposed approaches together with the formal treatment and with the simulative performance evaluation as the key contributions, we also see the results obtained for "plain" IEEE 802.11p-based systems as a valuable contribution for understanding the performance limits of a system without power or rate control.

For our future work, many issues need to be further investigated. We will explore in detail the complete parameter space of EMDV in accordance with the environment and will address complex scenarios with intersections and with multiple information originators. Eventually, power and rate control should jointly be treated for optimum performance of the vehicle-to-vehicle communication system, particularly in traffic scenarios with a very high vehicle density, e.g. in traffic-jam situations. In such scenarios, for instance, it might be better to first reduce the beacon rate (because the velocity of the vehicles and the rate of topology changes are relatively small) and then reduce the transmission power to control the load on the wireless channel.

APPENDIX
D-FPAV ANALYSIS

Theorem 1: Assume that the CS ranges of the nodes are symmetric, i.e., $u_i \in \mathrm{CS}_{MAX}(j) \Leftrightarrow u_j \in \mathrm{CS}_{MAX}(i)$, and that the number of nodes within range CS_{MAX} of each network node does not change. Then, the D-FPAV algorithm computes an optimal solution to BMMTxP within the time of two successive periodic beacon transmissions, i.e., the time of two successive broadcast transmissions that contain a node's local power computation.

Proof: First, we have to show that, under the theorem assumptions, the PA computed by D-FPAV after one round of communication is a feasible solution to BMMTxP. Assume the contrary, i.e., assume that there exists node u_i such that $BL(\mathrm{PA}, i) > \mathrm{MBL}$, where PA is the power assignment computed by D-FPAV. This condition means that node u_i has many interferers, all of which are located in $\mathrm{CS}_{MAX}(i)$ (assuming symmetric CS ranges). Let $u_j, \ldots, u_{j+h}$, for some $h > 0$, be these interferers and let PA_i be the PA computed by node u_i for all the nodes in $\mathrm{CS}_{MAX}(i)$. In Step 1 of D-FPAV, u_i computes an optimal solution PA_i to BMMTxP restricted to $\mathrm{CS}_{MAX}(i)$. Assuming symmetric CS ranges, this solution includes a power setting for the interferers $u_j, \ldots, u_{j+h}$, and this power setting is such that $BL(\mathrm{PA}_i, i) \leq \mathrm{MBL}$. In Step 2 of D-FPAV, the power setting PA_i is disseminated to all nodes in $\mathrm{CS}_{MAX}(i)$, which includes all the interferers $u_j, \ldots, u_{j+h}$. Hence, each of the interferers receives from node u_i a power setting PA_i such that the condition on the beaconing load is not violated at node u_i. Because the final power setting of the interferers is at most PA_i (this instance follows from the minimum operation executed in Step 3 of D-FPAV) and the number of nodes within range CS_{MAX} from u_i are not changed and assuming a monotonic CS range,[14] we have that the beaconing load at node u_i cannot exceed the MBL threshold, which leads to a contradiction. This result proves that the PA computed by D-FPAV is a feasible solution to BMMTxP.

Let us now prove that the computed PA is optimal. Let PA be the power assignment computed by D-FPAV after all power computations by surrounding nodes have been received, and let $p_{\min}$ be the minimum of the node power levels in PA. Assume that PA is not optimal, i.e., there exists another feasible solution PA' to BMMTxP such that the minimum of the node power levels in PA' is $p' > p_{\min}$. Without loss of generality, assume that PA' sets the power level of all nodes in the network to p'. PA' is feasible; thus, we have that $BL(\mathrm{PA}', i) \leq \mathrm{MBL} \forall i \in 1, \ldots, n$. Hence, given the monotonicity of the CS range, every node u_i in the network computes a power setting $P_i \geq p'$ in Step 1 of D-FPAV (this instance follows from the water-filling principle used in the FPAV algorithm). The solution computed at Stage 1 by each node is at least p'; thus, each node receives power values at least as large as p' in Step 2b of the algorithm. Hence, the final power setting of every node in the network, as computed by D-FPAV in Step 3, is at least $p' > p_{\min}$, which contradicts our initial assumption that the minimum of the

[14] Under this assumption, an increase in transmit power can only increase the CS range.

power levels computed by D-FPAV was $p_{\min}$. It follows that the solution computed by D-FPAV is optimal, and the theorem is proven. ■

Theorem 2: The D-FPAV algorithm has $O(n)$ message complexity.

The straightforward proof of the theorem is omitted.

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Marc Torrent-Moreno received the M.Sc. degree in telecommunications engineering from the Polytechnic University of Catalonia, Barcelona, Spain, and the Ph.D. degree in computer science from the University of Karlsruhe, Karlsruhe, Germany.

Since 2001, he has participated in several research projects concerning mobile networks as part of different companies and universities such as British Telecom; NEC Deutschland, Düsseldorf, Germany; DaimlerChrysler Research and Technology North America, Palo Alto, CA, the University of California, Berkeley; and the University of Karlsruhe. In 2007, he made a step toward product development and market analysis by joining A2C (a joint venture between Ficosa International, S.A. and Grupo Mecanica del Vuelo Sistemas, S.A.), where he has been the Business Development and Project Manager, working on the development of innovative telematic solutions for the automotive market. He has contributed more than 20 papers and has reviewed for several conference proceedings and journals.

Dr. Torrent-Moreno has been on the organizing committees of the 2005 and 2006 Third ACM International Workshop on Vehicular Ad Hoc Networks.

Jens Mittag (S'08) received the Diploma degree in computer science from the University of Karlsruhe, Karlsruhe, Germany. He is currently working toward the Ph.D. degree with the Decentralized Systems and Network Services Research Group, Karlsruhe Institute of Technology (KIT).

Before joining KIT as a student assistant in 2005, he was with the Process and Data Management, Engineering Research Group, Research Center for Information Technology, Karlsruhe. His research interests include mobile networks, simulation environments, and, more recently, the modeling of wireless lower physical layers.

Paolo Santi received the *Laurea* and Ph.D. degrees in computer science from the University of Pisa, Pisa, Italy, in 1994 and 2000, respectively.

Since 2001, he has been a Researcher with the Instituto di Informatica e Telematica del CNR, Pisa. During his career, he visited the Georgia Institute of Technology, Atlanta, in 2001 and Carnegie Mellon University, Pittsburgh, PA, in 2003. He has contributed more than 45 papers and one book on wireless ad hoc and sensor networking. His research interests include fault-tolerant computing in multiprocessor systems (during his Ph.D. studies) and, more recently, the investigation of fundamental properties of wireless multihop networks such as connectivity, topology control, lifetime, capacity, mobility modeling, and cooperation issues.

Dr. Santi is a Senior Member of the Association for Computing Machinery (ACM) and the ACM SIGMOBILE. He is an Associate Editor for the IEEE TRANSACTIONS ON MOBILE COMPUTING. He was a General Cochair of the Fourth and Fifth ACM International Workshop on Vehicular Ad Hoc Networks and a Technical Program Cochair of the Fourth IEEE Workshop on Wireless Mesh Networks. He is involved in the organizational and technical program committee of several conferences in the field.

Hannes Hartenstein (M'01) received the Diploma degree in mathematics and the Ph.D. degree in computer science from the Albert Ludwigs University, Freiburg, Germany.

He is a Full Professor of Decentralized Systems and Network Services with the Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany, and a Director of the KIT Steinbuch Centre for Computing. Before joining the University of Karlsruhe, he was a Senior Research Staff Member with NEC Europe. He was involved in the FleetNet—Internet on the Road (2000–2003) and NOW: Network on Wheels (2004–2008) Projects, which were funded in part by the German Ministry of Education and Research. He is currently actively participating in the European Union Seventh Framework Programme project PRE-DRIVE-C2X. His research interests include mobile networks, virtual networks, and information technology management.

Dr. Hartenstein has been a Technical Program Committee Cochair and General Chair of various highly selective ACM and IEEE international workshops and symposia on vehicular communications.