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Supporting real-time data traffic in safety-critical vehicle-to-infrastructure communication

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Abstract - **Support for real-time traffic is crucial to many ITS (Intelligent Transport Systems) safety applications. At the same time it is desirable to provide a number of non-safety services. In this paper, we propose a communication system for safety-critical V2I (Vehicle-to-Infrastructure) communication based on an extension to the upcoming IEEE 802.11p MAC standard. Real-time analysis provides the tool to adapt the resources set aside for collision-free, safety-critical data traffic to the communication needs of the current number of supported vehicles. The remaining bandwidth is available to other services according to the contention-based random access method defined in the standard. The performance of the proposed concept is evaluated through a simulation analysis based on a merge assistance scenario supported by roadside infrastructure.**

Keywords – IEEE 802.11p; inter-vehicle communication; medium access control; real-time communication; Quality of Service; vehicle-to-infrastructure communication.

I. INTRODUCTION

A reduction of fatalities and financial loss due to traffic accidents is a common goal of ITS (Intelligent Transport Systems) research. The introduction of communication technology plays a vital role in the development of proactive ITS safety applications. It enables vehicles to receive data that help both the vehicle itself and its driver to correctly assess the current traffic situation and its potential hazards. Information is shared between vehicles through inter-vehicle communication, either vehicle-to-vehicle (V2V) or vehicle-to-infrastructure (V2I), the latter involving an access point called road side unit (RSU). While a multi-hop, V2V communication system still lies further in the future, the introduction of strategically placed RSUs along highways can soon be reality.

Dedicated Short Range Communication (DSRC) is considered a key enabling technology for proactive ITS safety applications. The entire DSRC protocol stack is subject to the WAVE (Wireless Access for Vehicular Environments) standardization process conducted by the IEEE 1609 working group, while the physical and link layers are currently being standardized as IEEE 802.11p [1], a variation of the IEEE 802.11 Wireless LAN standard.

Proactive ITS safety applications share a demand for reliable and efficient communication. Support for real-time data traffic with guaranteed delay bounds is crucial if drivers should rely upon the application to help them avoid or react properly in critical situations. Besides safety-related data, it is desirable to reserve bandwidth for other, non-safety services that encourage user adoption and partly bear development costs.

As pointed out in the studies of Bilstrup et al. [2] and Eichler [3], the lack of support for real-time data traffic is a major shortcoming of the proposed WAVE standard. In this paper, we propose a deterministic Medium Access Control (MAC) scheme for V2I communication by extending the 802.11p standard with a collision-free communication phase controlled by an access point (in our case the RSU), as provided in other 802.11 WLAN standards. Safety-critical, real-time data traffic is scheduled in a collision-free manner by the RSU. The remaining bandwidth is available to other (best-effort) services according to the contention-based random access scheme defined in IEEE 802.11p. Real-time scheduling analysis is used to adapt the bandwidth dedicated to safety-critical real-time traffic to the current number of communicating vehicles and their communication needs, while thereby maximizing the possible amount of best effort traffic in the network.

The upcoming WAVE standard assumes a dedicated frequency band that allows the establishment of seven parallel frequency channels. Control and safety data with specific timing requirements are thereby separated from best-effort service data. Mak et al. [4] propose a solution for V2I communication including a polling-based phase for safety data exchange followed by a phase for non-safety service data traffic. The authors’ solution provides no real-time guarantees and assumes a number of separate safety and service channels. In Europe, however, the current dedicated ITS frequency band only allows for two simultaneous channels [5]. Our solution assumes therefore, that all types of data traffic share one frequency channel per driving direction.

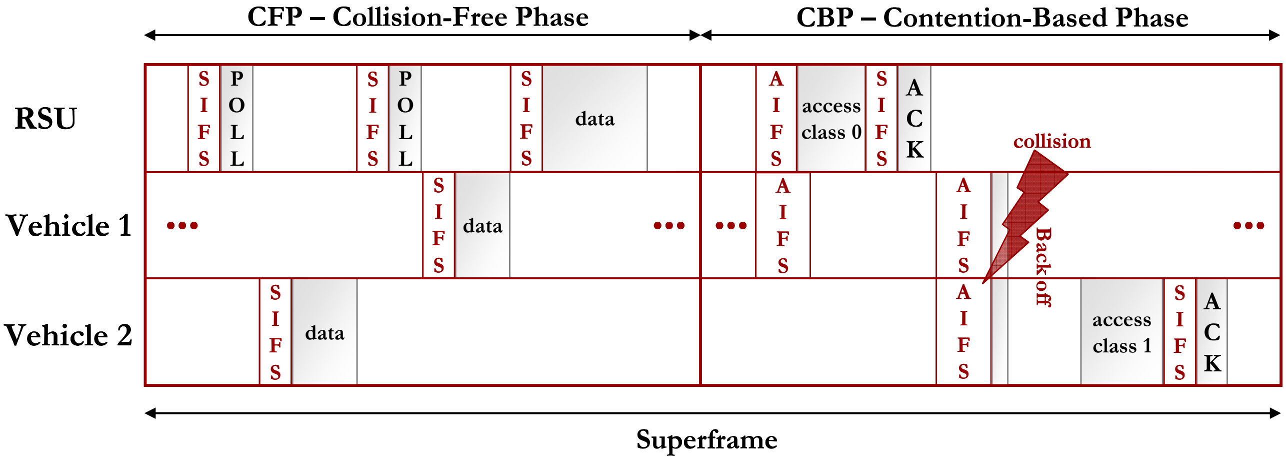

Figure 1: Collision-free and contention-based MAC in IEEE 802.11e.

An 802.11e-based scheduling approach with real-time guarantees is described by Fallah et al. [6]. An access point comparable to a RSU is used to control the traffic during the collision-free phase of 802.11e. As their solution is not aimed at vehicular networks, the authors assume a less dynamic network topology and do not use their scheduling analysis to adapt the length of the collision-free phase as intended in our solution.

The kind of real-time schedulability analysis used in this paper was first introduced by Spuri [7] [8] and originally developed for processor task scheduling. Recently, the analysis was successfully applied to the area of real-time communication, e.g., to industrial communication systems [9]. To our knowledge, however, it has not yet been adopted to support safety-critical real-time data traffic in a dynamic, 802.11-based network.

This paper is organized as follows. Section II gives a system overview and a background on 802.11e and 802.11p MAC. The protocol description in section III introduces our protocol and the underlying real-time schedulability analysis, while the simulation-based protocol evaluation is presented in section IV. Simulation results are based upon assumptions for a merge assistance scenario at a highway entrance, which can be considered representative for a general type of V2I applications where delay-sensitive data need to be supported while maximizing the amount of best-effort traffic in the network. In section V, the paper is concluded with a final discussion and an outlook on future works.

II. SYSTEM OVERVIEW

The 802.11p MAC protocol is equivalent to the 802.11e Enhanced Distributed Channel Access (EDCA) with QoS support [10]. In contrast to other 802.11 WLAN standards (e.g. 802.11a, b or e), the proposal for the upcoming 802.11p standard does not provide an additional, optional collision-free phase, controlled centrally by an access point through polling. Therefore, this in ITS applications well-needed option for real-time support is not present. We propose an extension to 802.11p by reintroducing the collision-free phase. This can be achieved by placing a real-time layer on top of the 802.11p MAC layer. This real-time layer takes care of the real-time data traffic before handing down best effort packets to the 802.11p MAC protocol.

In the rest of the paper, we assume that both a contention-based and a collision-free phase are present. In this section, these phases are explained more thoroughly and details on the proposed system design are given.

A. IEEE 802.11p and 802.11e MAC

In IEEE 802.11, time is divided into superframes, each consisting of a contention-based phase and a collision-free phase. Fig. 1 visualizes the concepts described below.

In the ***contention-based phase***, *CBP*, nodes compete for the access to the medium according to the CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) MAC method. Before starting a transmission, a node senses the medium until it is found to be idle. After an additional waiting time (Inter Frame Spacing), a transmission attempt can be started. Collisions occur when two or more nodes happen to start sending at the same time. A randomized back-off time is enforced on those nodes and a new transmission attempt is started.

The upcoming IEEE 802.11p MAC method is based on 802.11e with QoS support, where four different access classes are provided. The size of the contention window (the interval used to randomly choose the back-off time) and the size of the Arbitrary Inter Frame Spacing (AIFS) are used to enforce the channel access of the highest access class. The higher the priority (i.e. the lower the access class), the smaller is the contention-window and the AIFS. Despite the differentiation according to QoS demands, collisions within an access class are still possible and therefore, no timing guarantees can be given.

The ***collision-free phase***, *CFP,* needs support from an access point (the RSU) that takes responsibility for scheduling the traffic and polling the mobile nodes for data. A node is thereby assigned the right to use the channel without competition for a specified amount of time. A RSU can assign these rights to itself without polling. A short waiting time before transmission, the Short Inter Frame Spacing (SIFS), is defined for this phase. As no collisions occur, this access method is deterministic and therefore suitable for the delay-sensitive real-time data traffic needed in many ITS safety applications.

B. System Design and Architecture

The proposed system is based on a scenario, where a RSU is present and both safety-critical and non safety-critical data traffic have to coexist in the network. A highway entrance with a fixed RSU that provides passing vehicles with real-time merge assistance and best-effort road traffic information is one possible application scenario. Another application example is an accident-prone pedestrian crossing or a temporarily set up access point at an accident or road work site, where some of the bandwidth for ongoing best-effort ad-hoc communication is sacrificed to support warning or guidance messages with real-time guarantees.

In Europe only 20-30 MHz, i.e., two to three channels à 10 MHz, are planned to be set aside for ITS applications. For reasons of interference, this only provides a maximum of two simultaneous channels instead of the seven channels assumed in the standard. These two channels can be used as one control and one data channel or as two simultaneous data channels. In the transmission range of a RSU, it is therefore realistic to assume one channel per driving direction, shared by all data traffic (real-time and best effort) in the network.

The size of an 802.11 superframe is set as a system variable. Within a superframe, on the other hand, the ratio between the CBP and the CFP is not predetermined. The size of the CFP can therefore be dynamically adjusted during run-time, based on the actual number of communicating vehicles and their QoS demands. This information is gathered from periodic heartbeat messages sent out by vehicles inside the RSUs transmission range and used by the RSU for scheduling real-time data according to Earliest Deadline First (EDF) scheduling. The individual nodes are then polled for data during the collision-free period. Even safety-critical data from the RSU to the passing vehicles (unicast or broadcast) are scheduled. In this case, polling is of course unnecessary.

The remaining part of the superframe is shared by the best-effort traffic. How best-effort traffic is handled in the contention-based period does not directly influence our work. For the completeness of our system description, however, we assume a QoS-enhanced CSMA/CA MAC scheme proposed in both 802.11e and 802.11p. Due to the differentiated access classes, both ongoing V2V data traffic of high priority and services of lower priority (digital map updates, advertisements etc.) can be supported.

Further assumptions for our V2I communication system are a RSU transmission radius of around 400 m and a mechanism for vehicles to join the Basic Service Set (BSS), i.e., the group of nodes controlled by the RSU, without considerable delays. Due to the periodic nature of the assumed data traffic, acknowledgements (ACK) for successful packet transmissions of real-time data are not used. The periodic messages in our system are sent out with high update frequencies. In case of a lost packet, we argue that it is more reasonable to wait for the next packet instead of wasting resources on the retransmission of a packet with potentially outdated content. Typical parameter values can be found in section IV, where a merge assistance scenario is introduced for the simulation analysis.

III. PROTOCOL DESCRIPTION

A. Protocol Outline

Each data traffic class is defined by a period, a deadline, a maximum packet length and a direction of transmission (RSU to vehicle, *RSU→V*, or vehicle to RSU, *V→RSU*). Based on this information, the RSU schedules all packets for the next superframe according to EDF and queues them for transmission. Packets from the vehicles to the RSU, *V→RSU*, are of course not physically available for queuing and are replaced by a placeholder (similar to the concept of virtual packets described in [6]) including information about both data packet, polling packet and delays associated with the polling process.

A minimum of 20% of the superframe will be set aside for the best-effort data traffic as the CBP. Using the real-time schedulability analysis described later in this section, we can check if the remaining bandwidth of the CFP can support the demand for real-time data traffic, i.e., if we can guarantee that no safety-critical packet misses its deadline. This is done according to the algorithm shown in Fig. 2. With a maximum CFP of 0.8 times the length of the superframe, the feasibility for the current number of vehicles is checked. A positive outcome leads to a reduction of the CFP (e.g., by 0.001) before the feasibility check is run again. This is repeated until the minimum size CFP is determined that still supports all real-time data traffic present in the network. To reduce the computational demands on the system, a binary search algorithm provides an alternative solution.

```
CFP = 0.8 * superframe
if (feasibility check == true)
    while (feasibility check == true)
        CFP = CFP – reduction_step
    end
else
    CFP = CFP + reduction_step
end
```

Figure 2: Adjustment algorithm.

TABLE 1
LIST OF PARAMETERS

BP	Busyperiod (s)
CBP	Length of CBP (bits)
CFP	Length of CFP (bits)
$CFP_{percent}$	Percentage of SF used for CFP
$d_{blocking}$	Delay due to blocking packet (s)
d_{prop}	Worst case propagation delay between RSU and mobile node
d_{SIFS}	Delay due to SIFS (s)
D	Original deadline for a RT packet (s)
D_{CFP}	Adapted deadline for a RT packet (s)
E	Adjusted (experienced) transmission time of a RT packet (s)
$h(t)$	Workload function
HP	Hyperperiod (s)
$L_{RSU\to V}$	Length of a $RSU\to V$ packet (bits)
$L_{V\to RSU}$	Length of a $V\to RSU$ packet (bits)
L_{poll}	Length of polling packet (bits)
P	Period (s)
Q	Number of RT channels
R	Bit rate (bit/s)
R_{CFP}	Adjusted (experienced) bit rate (bit/s)
SF	Length of superframe (bits)
T	Total transmission time (s)
$T_{RSU\to V}$	Total transmission time of a $RSU\to V$ packet (s)
$T_{V\to RSU}$	Total transmission time of a $V\to RSU$ packet (s)
U	Utilization

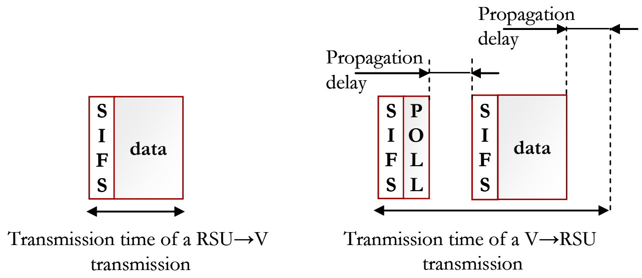

Figure 3: Total transmission times for RSU→V and V→RSU data

B. Definitions and Timing Analysis

At any point of time, a total number of Q different, logical real-time (RT) channels are present (including both $RSU\to V$ and $V\to RSU$ data traffic), defined by source, destination, period P_i, packet length L_i and a delay bound D_i, where $1 \le i \le Q$. See Table 1 for a list of variables used in this section.

The packet length of a data packet for $RSU\to V$ and $V\to RSU$ data traffic, including the packet header, is denoted $L_{RSU\to V}$ and $L_{V\to RSU}$, respectively. $V\to RSU$ data traffic is initiated by a polling packet from the RSU, while data from the RSU to the vehicles, $RSU\to V$, is sent without polling. This has to be accounted for in the analysis (see Fig. 3). Any packet transmission is always preceded by a waiting time, the Short Inter Frame Spacing (SIFS). This delay, d_{SIFS}, is set as a system parameter. The total transmission time of a $RSU\to V$ packet includes therefore $L_{RSU\to V}$ and the corresponding d_{SIFS}:

$$T_{RSU\to V} = \frac{L_{RSU\to V}}{R} + d_{SIFS} , \tag{1}$$

where R denotes the bit rate. The total transmission time, $T_{V\to RSU}$, of a $V\to RSU$ transmission contains an additional polling packet from the RSU, L_{poll}, the SIFS delay, d_{SIFS}, and propagation delay, d_{prop}, of the polling packet and the data packet. $T_{V\to RSU}$ can therefore be written as:

$$T_{V\to RSU} = \frac{L_{V\to RSU} + L_{poll}}{R} + 2d_{SIFS} + 2d_{prop} . \tag{2}$$

The total transmission time, T_i, of a packet belonging to RT channel i, is set using either Equation 1 or 2, depending on the type of RT channel. For the scheduling analysis, no propagation delays need to be included in $T_{RSU\to V}$ since two consecutive packets from the RSU (two $RSU\to V$ data packets or one $RSU\to V$ data packet and one poll packet) just need a SIFS in-between. For the end-to-end delay, however, the propagation delay always needs to be considered as explained later in this section.

As stated above, a superframe, SF, consists of a contention-based and a collision-free phase, with the duration CBP and CFP respectively:

$$CBP = SF - CFP . \tag{3}$$

Only the collision-free phase, CFP, can be used for transmitting real-time packets. At the end of the CFP, there might not be enough time for a full packet to be scheduled. This is accounted for by reducing CFP by $d_{blocking}$, the transmission time of the longest packet specified by any RT channel:

$$d_{blocking} = \max_{i=1}^{Q}(T_i) . \tag{4}$$

Only a fraction $CFP_{percent}$ of the total bandwidth is available for RT traffic:

$$CFP_{percent} = \frac{CFP - d_{blocking}}{SF} \qquad (5)$$

To accommodate for this reduction in bandwidth, the original bit rate, R, is reduced to an experienced bit rate of R_{CFP} accordingly:

$$R_{CFP} = R \cdot CFP_{percent} \; . \qquad (6)$$

The experienced transmission time, E_i, of a real time packet is therefore defined as:

$$E_i = \frac{T_i}{CFP_{percent}} \; . \qquad (7)$$

Even if a packet has the shortest deadline and is placed first in the queue, its immediate transmission may be delayed by a *CBP*. If the remaining time before the start of a *CBP* is too short to accommodate the transmission of the packet, the waiting time is increased further by T_i. An additional worst-case blocking delay, $d_{blocking}$, due to an ongoing lower-priority packet transmission must be considered. The original deadline, D_i, of a packet (*RSU→V* or *V→RSU*) is therefore reduced to an adapted deadline, $D_{CFP,i}$, by subtracting the length of a contention-based phase, *CBP* and the worst-case blocking time, $d_{blocking}$ (see Fig. 4). Since the propagation delay is not included in T_i for *RSU→V* traffic, this must be considered when calculating $D_{CFP,i}$:

$$D_{CFP,i} = \begin{cases} D_i - CBP - d_{blocking} - T_i - d_{prop} & \text{if} \quad RSU \rightarrow V \\ D_i - CBP - d_{blocking} - T_i & \text{if} \quad V \rightarrow RSU \end{cases} \qquad (8)$$

C. Real-Time Schedulability Analysis

Assessing the feasibility of the allocation of RT channels over the common radio link is done in two steps. A necessary, but not sufficient, condition is that the utilization *U* of the link must never exceed 1. According to EDF scheduling theory [11], the utilization of periodic real-time traffic is:

$$U = \sum_{i=1}^{Q} \frac{E_i}{P_i} \; . \qquad (9)$$

The second step of the feasibility check introduces the workload function h(t). The following concepts need to be defined:

- The hyperperiod HP is the least common multiple of all periods of the RT channels, i.e. the length of the time interval from a common starting point of all tasks' periods to the point of the next common starting point.
- The busyperiod BP is any interval within the HP during which the link is not idle.

The workload function *h(t)* is calculated as the sum of the transmission times for all packets of all RT channels with an absolute deadline less than or equal to a point in time *t*, where *t* signifies the number of time units elapsed since the beginning of the *HP* [7] [8]. The workload *h(t)* is calculated as follows:

$$h(t) = \sum_{i=1}^{Q} \left(1 + \left\lfloor \frac{t - D_{CFP,i}}{P_i} \right\rfloor \right) \cdot E_i \; . \qquad (10)$$

The second condition of the feasibility check is given by:

$$h(t) \leq t \; , \qquad (11)$$

where the number of instances of evaluation can be reduced to the instances of *t* where a deadline occurs and that fall into the first BP in the first HP of the schedule where all periods start at time zero.

IV. PERFORMANCE EVALUATION

The performance of our proposal is evaluated by simulation of an infrastructure-based merge assistance scenario. The co-existence of safety-critical data with strict timing requirements and non-safety-critical, best effort data makes the merge assistance case a representative of a wide range of typical ITS safety scenarios.

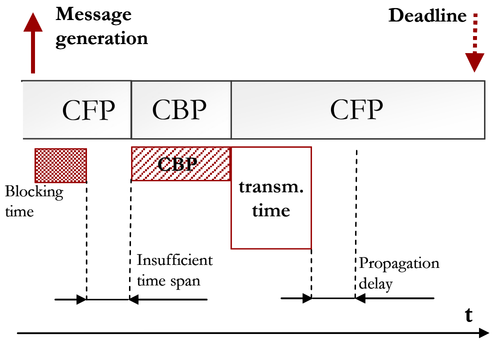

Figure 4a: Delay bound analysis**.**

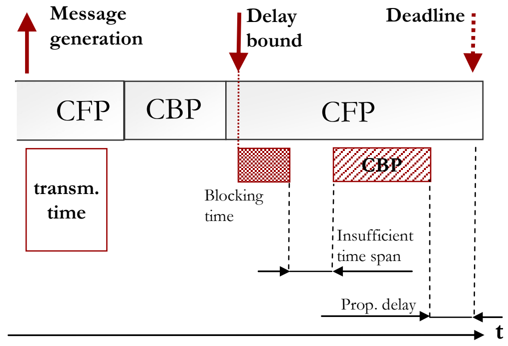

Figure 4b: The original deadline is adjusted to the new deadline.

A. Merge Assistance Scenario

Merging into a flow of heavy traffic at a highway entrance is a common source of traffic accidents. The merge assistance scenario is based on V2I communication involving a RSU at a highway entrance that supports both entering and passing vehicles with heterogeneous communication services covering a variety of Quality of Service (QoS) requirements.

For cost reasons, initially, a seamless coverage of the highway network with access points cannot be expected. Therefore, V2I-based data exchange is concentrated to hot spots like highway entrances that are covered by a RSU. The RSU collects merge-related data from the mobile nodes and broadcasts recommendations concerning the merging process back to them. Vehicles passing a RSU might want to collect road traffic information while passing the access point to get an update on, e.g., current road, traffic or weather conditions. At the same time, different best-effort data traffic classes should be supported. The assumed data traffic classes are described below and summarized in Table 2.

- ***Merge heartbeats***
  Short, periodic heartbeat messages stating a vehicle's speed, position, length, turning signal activities etc. [12]. These packets are periodically sent from the mobile nodes to the RSU. Merge heartbeats are considered safety-critical and deadlines must not be missed.
- ***Merge recommendations***
  Based upon the collected data from the heartbeat messages, the RSU computes merge recommendations which are periodically broadcasted back to the vehicles where the information will be used by the system or presented to the driver as appropriate warnings or recommendations. Merge recommendations are safety-critical and deadlines must be met.
- ***Road information updates***
  Information about, e.g., traffic conditions, accidents or roadwork sites as well as weather and road condition data need to be sent to passing vehicles. The update frequency for this type of messages is lower but must be high enough to ensure that each vehicle, even at high speed, receives at least one copy before it leaves the transmission range. Therefore, even this traffic class is considered safety-critical.
- ***Best-effort data traffic***
  This category comprises all kinds of ad hoc V2V communication that takes place without the knowledge and involvement of the RSU. It also includes RSU-based services like, e.g., digital map updates, advertisements or short downloads. Multimedia data for e.g. entertainment applications are not considered as these need more or less seamless RSU-coverage.

TABLE 2
DATA TRAFFIC CLASSES

	Safety-Critical	**Best-Effort**
Vehicle → RSU	▪ Merge heartbeat	
RSU → Vehicle	▪ Merge recommendation ▪ Road information updates	▪ Non-safety-critical RSU-based services
Vehicle → Vehicle		▪ RSU-independent V2V communication

B. Simulation evaluation

To evaluate the performance of our proposed MAC management method, a simulator was implemented in MatLab. Merge heartbeats (with a packet length of 500 byte, a period of 100 ms and a deadline of 100 ms), traffic information updates (with a packet length of 1.5 kbyte, a period of 1 s and a deadline of 100 ms) and merge recommendations (with a packet length of 1.5 kbyte, a period of 100 ms and a deadline of 100 ms) are the three safety-critical, real-time data traffic classes in the network. A fixed superframe of 100 ms is chosen throughout the simulations and a reduction step of 0.001 is used for our proposed algorithm. Table 3 gives the full list of parameter values the simulation results are based upon. The propagation delay of 0.01 ms includes delays at the sender and receiver.

TABLE 3
LIST OF SIMULATION PARAMETERS

RSU transmission radius	400 m
Minimum length of CBP	20 ms
Maximum length of CFP	80 ms
Superframe length	100 ms
Propagation delay	0.01 ms
Bit rate	6 - 24Mbit/s
SIFS delay	0.016 ms
Polling packet length	20 byte
Merge heartbeat: Packet length	500 byte
Merge heartbeat: Period	100 ms
Merge heartbeat: Deadline	100 ms
Traffic info update: Packet length	1.5 Kbyte
Traffic info update: Period	1000 ms
Traffic info update: Deadline	100 ms
Merge recommendation: Packet length	1.5 Kbyte
Merge recommendation: Period	100 ms
Merge recommendation: Deadline	100 ms
Reduction step	0.001

Fig. 5 shows the part of the bandwidth that is left for the best-effort data traffic for a certain number of accepted vehicles in the RSU's transmission range when all safety-critical real-time data packets are accommodated. Results for bit rates of 6, 12 and 24 Mbit/s are shown, approximately spanning over the achievable bit rates for 802.11p. We assume a minimum reserved bandwidth of 20% for best effort data traffic, i.e., for the CBP. This is indicated by a threshold line in the figure. With this CFP/CBP-ratio of 80/20, 82 vehicles can be accommodated at a bit rate of 6 Mbit/s, 160 vehicles at a bit rate of 12 Mbit/s and 292 vehicles at a bit rate of 24 Mbit/s. A number of 80 vehicles within the transmission range (which can be considered dense traffic even on a 3-lane or 4-lane highway) would lead to approximately 21% of the bandwidth left for best-effort traffic at 6 Mbit/s, 43% at 12 Mbit/s and 58% at 24 Mbit/s.

Fixed bit rates of 6 Mbit/s for Fig. 6 and 24 Mbit/s for Fig. 7 are used to show the average vehicle spacing resulting from a certain CFP/CBP-ratio. An average vehicle length of 5 m, not included in the inter-vehicle distance, is assumed. A graph for a highway with 2, 3 or 4 lanes per driving direction is shown respectively, which corresponds to 1 600, 2 400 or 3 200 m of road for the vehicles to share. For the bit rate of 6 Mbit/s in Fig. 6 and a 3-lane highway scenario, the threshold of 20% for best-effort data traffic leads to an average vehicle spacing of 24 m. As shown in Fig. 7, a bit rate of 24 Mbit/s

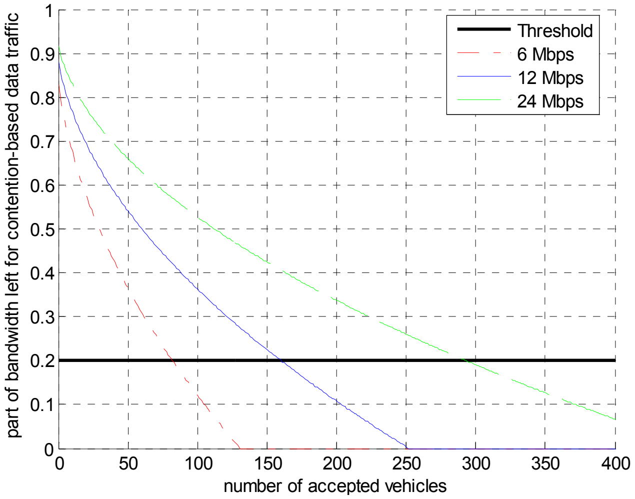

Figure 5: Fraction of bandwidth left for best effort (contention-based) data traffic for various numbers of accepted vehicles.

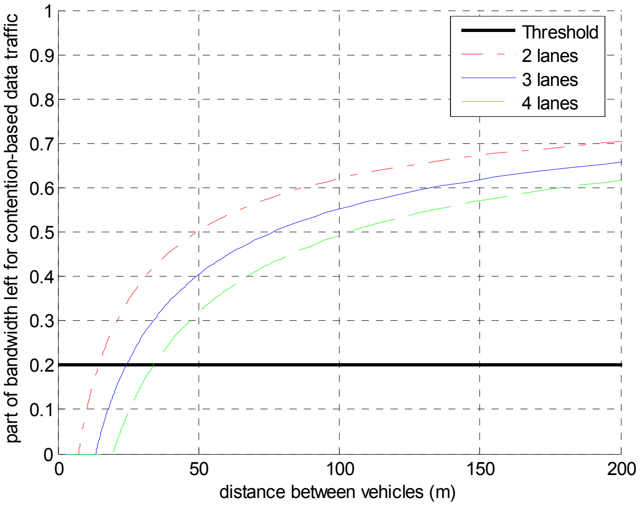

Figure 6: Fraction of bandwidth left for best effort (contention-based) data traffic for various average inter-vehicle spacings. Bit rate: 6 Mbit/s.

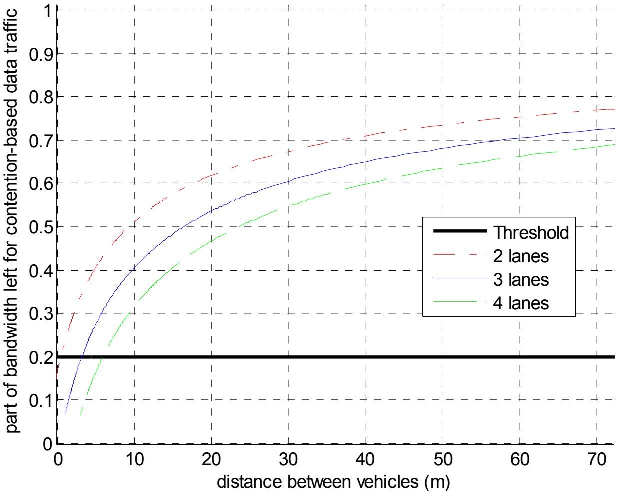

Figure 7: Fraction of bandwidth left for best effort (contention-based) data traffic for various average inter-vehicle spacings. Bit rate: 24 Mbit/s.

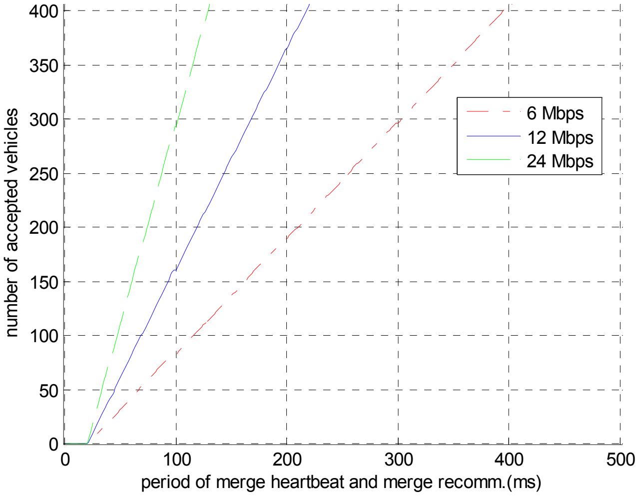

Figure 8: Number of accepted vehicles for various update periods for merge heartbeat and merge recommendation

gives an average vehicle spacing of around 3 m for the same 3-lane highway and the same 20% CBP threshold value. These results show that our solution is able to support real-time data traffic and a reasonable amount of best-effort data traffic even for very high vehicle densities experienced in e.g. a traffic jam situation.

In Fig. 8, the update period of merge heartbeat and merge recommendation messages was varied between 1 and 500 ms. On the y-axis, the corresponding number of accepted vehicles can be seen. Increasing the update period, i.e., the time span between the generation of periodic messages, by a factor 2 leads to an increase in accepted vehicles by approximately a factor 3. This shows that an adaptation of the update frequency to the current mobility of the vehicles (i.e. their average velocity) can further improve the performance of the system.

V. CONCLUSION

In this paper, we presented a communication system for safety-critical V2I communication, extending the upcoming IEEE 802.11p MAC standard with a polling-based, collision-free phase for real-time data traffic. Real-time schedulability analysis is used to reduce the collision-free phase to a minimum, while still supporting the timing requirements of all real-time channels. The remaining bandwidth is used for best effort data traffic.

Our simulation results show that the proposed algorithm is suitable for the bit rates supported by the 802.11p standard and the traffic capacity expected from a 2 – 4 lane highway. Fine-tuning the bit rate and the update frequency of the periodic data packets depending on the actual vehicle density and average vehicle velocity can further increase the amount of bandwidth left for best effort traffic classes.

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