MCB - A Multi-Channel Beaconing Protocol

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Abstract

We present Multi-Channel Beacon (MCB), a novel approach for efficient wide area data dissemination in vehicular networks using all the DSRC/WAVE channels. Current standardization efforts towards beaconing (i.e., one-hop broadcasting) protocols in vehicular networks focus on the use of a single radio channel only. This is a major bottleneck at high vehicle densities, leading to high delays or packet loss. Instead, the main focus has been to use adaptive transmit rates in order not to overload the wireless channel. Based on our previous work towards multi-channel operation, we developed a novel approach, MCB, which provides adaptivity not only in time, i.e., congestion control, but also in space by selecting appropriate channels for upcoming data transmissions. We evaluated our approach in simulations, comparing our solution to state of the art beaconing protocols, most importantly to the current ETSI Decentralized Congestion Control (DCC) standard. Our results clearly demonstrate the feasibility of our multi-channel approach, showing that it successfully reduces channel utilization and observed packet collisions without sacrificing goodput.

Key words: vehicular networks, multi-channel, beaconing protocol, performance

1. Introduction

Intelligent Transportation Systems (ITS) primarily rely on efficient communication concepts [1]. In the last few years, much progress has been made in the field of Inter-Vehicle Communication (IVC), leading to industry standards that define both the physical and the access layer for Dedicated Short Range Communication (DSRC) like IEEE 802.11p and IEEE 1609.4 [2, 3] or ETSI ITS-G5 [4]. Based on this radio access technology, different concepts for information dissemination have been explored. This started with simple messages to be broadcast periodically. Such one-hop broadcasts have been termed *beacons*, were later standardized as Cooperative Awareness Messages (CAMs) [5] and Basic Safety Messages (BSMs) [6], and are now thought to be the main communication primitive for a wide range of IVC applications.

In order to enable CAMs/BSMs in all possible scenarios, e.g., during rush hour or in traffic jams with hundreds of cars in communication range but also in very sparse scenarios at night time, the inter-packet interval has been identified as the most critical parameter to adapt [7, 4, 8, 9, 10]. The main objective of such adaptive beaconing is to minimize the communication delay while keeping the wireless channel use well below its capacity to avoid packet collisions. The presented concepts rely on a single wireless channel making use of either the DSRC Control Channel (CCH) or one of the Service Channels (SCHs).

In this paper, we study the feasibility of using multiple channels at the same time in a Single-Radio Multi-Channel (SR-MC) fashion. In particular, we created a novel multi-channel beaconing approach, called the Multi-Channel Beacon (MCB) protocol. The presented work has evolved from our previous work presented in [11], now employing a novel concept for channel scheduling that exploits emergent behavior. This approach substantially reduces the channel utilization and observed packet collisions without sacrificing goodput, while at the same time increasing reliability. Furthermore, we show that MCB also reduces the inter beaconing interval, together with a lower channel utilization, compared to single-channel approaches. Although we take a traffic efficiency application as example, the presented approach can be applied to any other application requiring information dissemination in vehicular networks. Our evaluation shows that the use of multiple channels is not only feasible but also leads to substantial performance improvements.

Our main contributions can be summarized as follows:

- We present a novel Single-Radio Multi-Channel (SR-MC) beacon scheduling system for vehicular networks that follows a split phase approach.
- We show how MCB can keep channel coordination overhead low by relying on a careful selection of when to send coordination information.
- Using a traffic information system as an example, we clearly show that the use of multiple channels not

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only reduces the load of the wireless channel(s) but also lowers the information dissemination delay as required for safety applications.

2. Related Work

We classify related work on this topic into two categories, namely Traffic Information System (TIS) protocols for IVC using beaconing and approaches to multi-channel scheduling systems for both single-radio and multi-radio environments.

Regarding TIS protocols, the usage of CAMs [5] and BSMs [6] represents the simplest form of information dissemination via beacons. Here, to improve situational awareness, these beacons contain information about the current speed and driving direction of vehicles.

SOTIS [12] goes one step further: at its core are knowledge bases (one is being maintained on each vehicle) which integrate any received traffic information items; selected parts of these knowledge bases are periodically assembled into beacons and broadcast to neighboring vehicles.

It was found that static periodic beaconing is not suitable for every road traffic scenario, since the wireless channels easily get overloaded in case of traffic congestions with many vehicles simultaneously distributing their information. At the same time, in very sparse scenarios, the beacon interval might be too large to exploit the few communication opportunities and disseminate information in a timely manner.

REACT [13], to best of our knowledge, is the first protocol which proposes a dynamic beaconing approach, where the interval between two consecutive beacons is adapted to the density of the road network.

Adaptive Traffic Beaconing (ATB) [7] extends this approach by proposing a novel prioritization scheme, where the inter-packet interval depends on the channel quality and the priority of the traffic information. The goal of ATB is to send as many information as possible, but avoid overloading the wireless channel at any time. Similar concepts have also been investigated in [8, 9] as well as in the ETSI ITS-G5 standardization group [4].

FairDD [14] considers another topic on information dissemination. Most of the protocols for IVC rate information based on sender side metrics which in fact does not represent a realistic road network, where a receiver maybe is interested in information which is near irrelevant for a sender. To maximize the overall message utility (i.e., transmitting only the information which is most interesting for receiver) is a key challenge in vehicular networks, where FairDD provides an algorithm using Nash Bargaining.

FairAD [15, 16] successfully combines the two approaches for fair and efficient information dissemination of FairDD and ATB, respectively, while retaining the advantages of both. However, it still operates on a single channel only, leaving room for further improvements.

In the context of multi-channel scheduling approaches, the problems and pitfalls of wireless communication both for SR-MC and Multi-Radio Multi-Channel (MR-MC) systems have been described in [17]. The authors in [18] study the complexity of channel scheduling for MR-MC in a theoretical way and prove that it is NP-hard under different interference models. The question of how the capacity of such a network scales with increasing number of nodes has been studied in [19].

In [20] the authors study dynamic channel intervals instead of fixed ones for the use in IEEE 1609.4. They divide the CCH interval into three phases to support service announcements, status beacons and peer to peer communication resource reservation, but they do not provide channel selection algorithms.

In [21] a multi-channel MAC protocol is proposed which uses two phases in the CCH interval to provide a time window for time slot reservation on a SCH and the CCH, as well as collision free access for messages in their reserved time slots. Their channel negotiation scheme consists of several packets to be exchanged by each vehicle to perform one negotiation step which adds additional channel load.

The authors in [22] study dynamic channel intervals using an analytical model. They divide the CCH interval into a safety and a service announcement interval which are dynamic according the traffic density. They do not focus on the SCH selection scheme.

In [23] an asynchronous multi-channel approach for DSRC is proposed which employs a channel negotiation scheme which uses a well-known SCH (instead of the CCH) to announce specific services, investigating the additional time needed for rendezvous in such a scheme.

In contrast to the presented multi-channel approaches, our protocol follows the beaconing principle, which lowers the complexity of channel negotiation – at no cost to the speed of information dissemination, as we will demonstrate.

3. Preliminaries

In this section, we briefly introduce IEEE 1609 WAVE and the Adaptive Traffic Beaconing (ATB) protocol that we used to manage the load on a a single wireless channel.

3.1. IEEE 1609 WAVE

In most countries that are envisioned to operate IVC services, more than one channel is available to participating vehicles. For example, in the U.S., up to seven channels are available, depending on the service offered [24] as illustrated in Table 1.

It is an open question how to best exploit multiple channels in an SR-MC system, where only one radio is

type	SCH	SCH	SCH	*CCH*	SCH	SCH	SCH
channel	172	174	176	178	180	182	184
GHz	5.860	5.870	5.880	5.890	5.900	5.910	5.920
dBm	33	33	33	44.8	23	23	40

Table 1: WAVE use cases and parameters adopted from [24]

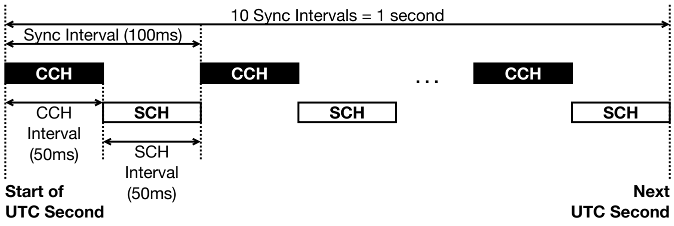


Figure 1: The principle of the WAVE Split Phase Protocol. A node periodically switches between the CCH and one of the available SCHs. Each node synchronizes its Sync-Intervals by GPS.

installed per vehicle that then needs to switch between channels. The IEEE 802.11p standard and IEEE 1609 DSRC/WAVE series of standards [2] aim to provide a comprehensive communication stack for IVC. IEEE 802.11p is an optimized variant of IEEE 802.11a with a dedicated frequency band at 5.9 GHz and modified timing values to meet the requirements of IVC.

For multi-channel operation, this WAVE stack adopts a split phase approach, where all nodes periodically switch to a well-known CCH at well-known instances in time to exchange service announcements, as illustrated in Figure 1. Individual services can then be provided on the announced SCH. One example implementation of the IEEE 1609.4 multi-channel system works as illustrated in Figure 1: All communications are synchronized every second by means of GPS. Afterwards, the radios continuously switch between the CCH and one of the SCHs in intervals of 50 ms. We discuss the impact of this switching in more detail later in the paper.

It is this stack our work builds on. We also adopt the split phase approach of IEEE 1609.4 [25], though MCB is not limited to be used with WAVE.

The main challenge of this multi-channel operation is that an application needs to select the time *when* to use *which* SCH to allow a robust and reliable communication with low interference. Furthermore, the aim of such an application protocol is to evenly utilize all SCHs to not overload a specific channel and to avoid the problems introduced by multi-channel operation, like the deafness and the multi-channel hidden terminal problems [17].

3.2. The ATB Protocol

Another open question is *how often* to best exchange information, such as not to overload the channel, yet deliver high information dissemination speeds – and *which* information to select for exchange when given the opportunity to broadcast a beacon to all present neighbors.

The single-channel ATB protocol, which we base our work on for this decision, consists of several parts [26, 7]. We begin our description with information storage on vehicles and the beacon interval calculation. Subsequently, we present the algorithms for determining the channel conditions and message priorities.

3.2.1. Knowledge Base Management

As is common, ATB stores received traffic information in a knowledge base, an ordered list of entries with traffic information items sorted according to an individually calculated priority. Every change in the knowledge base (e.g., received beacons causing a merge of information or new observed traffic events) causes a recalculation of the message utility (and thus the priority) of every entry.

A core idea of ATB is to suppress the sending of irrelevant information, so the knowledge base only stores information relevant for the vehicle (i.e., only the most recent information of a route segment). To perform this, each event (i.e., gathered from sensors within the vehicle or received in beacons from other nodes) either updates existing entries of the knowledge base or is appended to it. Furthermore, to limit the size of the knowledge base, a garbage collector removes entries after a defined timeout as they are deemed to be outdated and therefore no longer relevant.

When sending a beacon, ATB takes as much entries from the top of the list as there is room for in a single frame and sends them (i.e., the most important ones) as a broadcast on the CCH to other vehicles. Only sending one frame has the advantage that there is no need for managing fragmentation of messages. Further, the channel capacity is used more efficiently, because overhead is minimized: every frame consists of as much knowledge base entries as there is room.

A number of approaches to calculate the utility (and, hence, the target priority) of individual knowledge base entries exist in the literature, the most recent one being the one presented for FairAD [15]. Yet, for the sake of simplicity, we chose a sum considering the age of an entry and the proximity to the event origin, as presented in the original publication of ATB [7]. Accordingly, each knowledge base entry contains the type of event (e.g., *accident*), time stamp, location, priority, and an identifier of the affected road.

3.2.2. Beacon Interval Calculation

The beacon interval at which knowledge base entries are disseminated is in part derived from the *message utility* of the highest priority entry in the knowledge base. Again, possible approaches range from very recent schemes that are also able to capture metrics of fairness [15, 16], to the straightforward calculation presented in [7] used in this evaluation, which considers solely the age of an entry and current proximity to the event origin.

In any case the beacon interval calculation also considers a second class of metrics. As already mentioned in the sections before, ATB is designed to send beacons as often as possible, but to never overload the wireless channel to prevent any possible wireless collisions. This can be summarized as the *channel quality*.

Based on the message utility P, the channel quality C, a relative weighting w_I, and limits of the beacon interval $[I_{\min}, I_{\max}]$, the recommended beacon interval ΔI is calculated according to [7] as follows.

$$I = (1 - w_I) \times P^2 + w_I \times C^2 \quad (1)$$

$$\Delta I = I_{\min} + (I_{\max} - I_{\min}) \times I \quad (2)$$

The interval weighting factor w_I gives the channel metric a higher influence to the beaconing interval.

The calculation of the channel quality considers three metrics that correspond to channel capacity in the past, the current, and the future:

Past: To measure the channel load in the past, the observed packet collisions are counted. While this is straightforward to do in simulations, in practice packet collisions cannot be directly observed. However, they can be estimated in two ways (at the receiver side): First, if the received signal is strong enough to decode packets, but the receiver is not able to decode any information. Another possibility to measure packet collisions is by observing bit flips and differences in the checksum.

Present: To capture the current channel conditions, the signal quality during the last transmissions is taken as a metric. This gives a rough indication of the current channel quality.

Future: To predict any possible communication of other vehicles in the future, the amount of neighbors is estimated. Considering that every vehicle has a unique (potentially short-time) identifier which is appended to each beacon, the amount of individual nodes contending for the wireless channel within a predefined period of time can be measured.

4. MCB Protocol

In the following, we present our novel MCB protocol, which is specifically designed to take advantage of the additional SCHs available in the DSRC band. MCB works as a split phase Single-Radio Multi-Channel (SR-MC) protocol and can operate on top of other such protocols, e.g., IEEE WAVE. The protocol has evolved from our previous work on multi-channel information dissemination [11] (which, in turn, was based on ATB). The main difference of MCB is that we provide completely new algorithms and techniques to address the shortcomings introduced by split phase multi-channel operation like additional delays and split network topologies.

4.1. Multi-Channel Operation

In Figure 2 we show the principle of MCB and its operation on top of a split phase protocol. As in IEEE 1609 Wireless Access in Vehicular Environments (WAVE), time is divided into CCH and SCH intervals, separated by short guard intervals to mitigate synchronization inaccuracies. MCB broadcasts data announcements on the CCH, advertising the SCH where data will be transmitted during

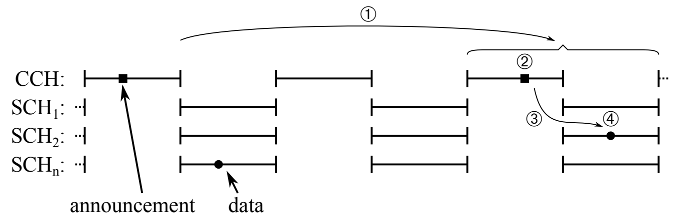


Figure 2: MCB operation in four steps: (1) coarse-grained interval selection, (2) selecting a time for the announcement, (3)selecting a channel and time for the data and sending an announcement, and (4) sending the data.

the following SCH interval, when nodes are free to leave the CCH and tune to the best available channel. Channel switching is only performed during guard intervals to minimize the probability of lost messages during channel switching.

MCB operation can be divided into four distinct steps: First, the beacon rate is regulated by adapting the number of intervals that elapse between beacon transmissions. Second, in intervals during which a beacon is to be transmitted, MCB carefully selects when to send a data announcement. MCB calculates this time t_{MCB} within the CCH interval to transmit the announcement according to the priority of the payload information such that more important messages are sent earlier in the interval. Third, at t_{MCB}, a node selects when and on which channel to transmit payload information, taking into account all received announcements up until this point, and sends an announcement. In a fourth step, after tuning its radio to the announced SCH during the guard interval between CCH and SCH, MCB selects when to send the data and broadcasts it.

4.2. Step 1: Coarse Grained Interval Selection

Split phase protocols like IEEE 1609.4 introduce additional delays when sending beacons on a SCH, since before the actual transmission can take place, the used channel has to be announced on the CCH during the corresponding interval. This leads to a delay between generating the information and putting it on the channel of up to 100 ms or more in the worst case (when trying to transmit information at the end of a CCH interval, the announcement is delayed by the 50 ms SCH interval and the following data transmission is delayed further by the 50 ms CCH interval). MCB takes this into account by employing the interval calculation of Equation (2) only for determining in which interval to send a beacon. For this, other than ATB which only monitored a single channel, MCB takes into account load on channels currently tuned to by taking the mean of the Signal to Noise plus Interference Ratio (SNIR) values of all SCHs and storing these values for the next calculations. The calculation of when in this interval to send the announcement and data is performed in a second step, described in the following section.

4.3. Step 2: When to Send the Announcement

After determining in which interval to transmit a beacon, MCB then determines at which time t_{MCB} in the interval to send the announcement. This announcement will indicate on which SCH data will be sent, so t_{MCB} is also the latest point in time when this decision can be taken. As channels are only switched during the guard interval between CCH and the selected SCH, the same SCH will be the one that data will be received on, requiring a trade-off between choosing a good channel for sending and a good one for receiving data. All in all MCB delays the announcement of a particular SCH as much as possible such that nodes can make better decisions on which channel to tune to. If the sending node picks a random SCH for transmitting the information, then it could happen with a high probability that the node misses some important information sent on a different SCH by other nodes.

MCB therefore chooses t_{MCB} according to the beacon priority based on the utility p of the most important entry of the knowledge base (measured in the interval $[0.0, 1.0]$, smaller values indicating more important beacons). In detail, t_{MCB} is calculated by first choosing

$$t_{\mathrm{p}} = 0.5 \times I_{\mathrm{switching}} \times p + I_{\mathrm{guard}}, \tag{3}$$

where $I_{\mathrm{switching}}$ and I_{guard} denote the respective intervals defined in [25], set to 50 ms and 4 ms, respectively. This defines the earliest time within the CCH interval at which the announcement might be sent, dependent on the priority. We use a value of 0.5 such that the lowest priority messages are delayed to the second half of the CCH interval. Next, the time left in the slot is calculated by

$$t_{\mathrm{left}} = I_{\mathrm{switching}} - t_{\mathrm{p}}. \tag{4}$$

Finally MCB uniformly distributes the beacon within the time left in the slot, limited by the defined factor f leading to the delay

$$t_{\mathrm{MCB}} = t_{\mathrm{p}} + \mathcal{U}(0, f) \times t_{\mathrm{left}}. \tag{5}$$

We define a factor $f = 0.5$ for messages with the highest importance and $f = 0.8$ otherwise. Together, these factors ensure that all announcements with the highest priority ($p = 0.0$) are sent before any announcement with the lowest priority ($p = 1.0$), linearly interpolating for priorities in-between. At the same time, they ensure that even for the highest delay enough time remains in the CCH interval.

Thus, whenever a node wants to transmit an announcement, it is able to take all announcements received up until t_{MCB} into account to decide on which SCH the information should be transmitted. By exploiting the emergent behavior following from this approach, MCB substantially reduces the need for explicit coordination messages.

4.4. Step 3: Selecting and Announcing an SCH

The idea to use channel metrics to decide which SCH fits better for transmitting information is quite common, but complicated to achieve. The reasons are as follows: a low utilized SCH on the sender side does not imply that this is also the best selection for a receiver due to the hidden terminal problem. Furthermore using status messages to get information of the channel states of neighboring nodes means additional channel utilization and therefore lowers the throughput of useful data messages. Another difficulty arises when we want to measure the channel utilization in a very small time frame, like an SCH interval. Since MCB is designed as a single-radio multi-channel protocol, it can only measure the channel utilization on the currently tuned channel. This requires channel measurements to be retained from the last time that the radio was tuned to the channel in question. Doing this is not very useful, because the network topology is likely highly dynamic and therefore the channel utilization can quickly change. We experienced the best results with the following channel selection algorithm:

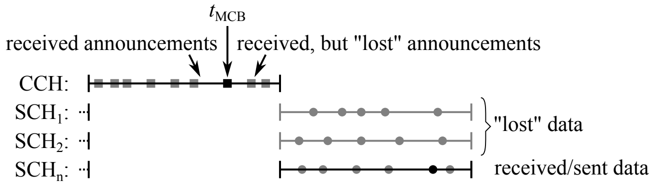


Figure 3: A node selects the best fitting SCH when an announcement is sent at t_{MCB}. Announcements received after this time are "lost" to the decision process. Similarly, data sent on other channels than the selected SCH is "lost" to the node.

A node which sends a beacon in the next SCH interval and thus needs to broadcast an announcement in the CCH for it, needs to select which channel to tune to no later than at time t_{MCB}. As illustrated in Figure 3, this means that only announcements received up until that point can be considered for SCH selection (in essence, all announcements received after t_{MCB} are "lost" to the decision process). Similarly, selecting an SCH for sending (and receiving) data means that all data on other SCHs is "lost" as far as the given node is concerned. Only for a node which does not intend to transmit a beacon in the next SCH interval, this decision can be postponed to the start of the guard interval of the SCH. Either when t_{MCB} approaches or when the guard interval of the SCH starts, the node calculates the set of all received announcements during the current interval until now leading to

$$\mathbb{W} = \left\{ \begin{pmatrix} \mathrm{channel}_1 \\ \mathrm{priority}_1 \end{pmatrix}, \begin{pmatrix} \mathrm{channel}_2 \\ \mathrm{priority}_2 \end{pmatrix}, \ldots, \begin{pmatrix} \mathrm{channel}_n \\ \mathrm{priority}_n \end{pmatrix} \right\} \tag{6}$$

and calculates the subset $\hat{\mathbb{W}}$ as those members with the highest priority (i.e., the lowest value of p) in $\mathbb{W}$:

$$\hat{\mathbb{W}} = \left\{ w \in \mathbb{W} : \mathrm{p}(w) = p_{\min} \right\}, \tag{7}$$

$$p_{\min} = \min_{v \in \mathbb{W}} \bigl(\mathrm{p}(v)\bigr), \tag{8}$$

where p(·) returns the priority of an individual announcement.

If MCB does not send a beacon, it chooses the channel that has been announced most often in $\hat{\mathbb{W}}$.

If it does send a beacon (with priority p_{self}), it first calculates a set of announcements of potential SCHs as

$$\mathbb{C} = \begin{cases} \hat{\mathbb{W}} & \text{if } p_{\min} < p_{\text{self}} \\ \emptyset & \text{else .} \end{cases} \quad (9)$$

This guarantees that, while a node with less important information is still allowed to send, it will not only do so much less often (following the procedure of Section 4.2), but it also cannot tune to a channel that would cause it to lose the more important information.

Finally the SCH c which it announces (and tunes to in the interval afterwards) is randomly drawn from $\mathbb{C}$ as

$$c = \begin{cases} \text{ch}(\mathcal{U}(\mathbb{C})) & \text{if } \mathbb{C} \neq \emptyset \\ \mathcal{U}\big(\{\text{SCH}_0, \text{SCH}_1, \ldots, \text{SCH}_{\max}\}\big), & \text{if } \mathbb{C} = \emptyset \text{ ,} \end{cases} \quad (10)$$

where ch(·) returns the announced channel of the selected announcement and $\mathcal{U}(\cdot)$ denotes selecting a set member according to a uniform probability distribution.

4.5. Step 4: Broadcasting the Data

After sending the announcement and switching to the selected SCH during the guard interval, all that is left is to transmit the data. The exact point in time when to transmit the data during the SCH interval is uniformly distributed along the whole interval to minimize the risk of collisions with other transmissions. In our case the data contains a subset of the node's knowledge base, taking as many entries as there is space in a single packet.

During the preceding and remaining time (during which the node stays tuned to the selected SCH), all received data can be integrated into the local knowledge base.

5. Performance Evaluation

In this section we investigate the performance gain of using our multi-channel beaconing protocol MCB compared to single-channel approaches. We introduce the baseline protocols used for comparison, the simulation scenarios, and the configured simulation parameters.

For the simulation experiments, we use the Veins[1] simulation framework [27]. Veins relies on fully-detailed models of IEEE 802.11p and IEEE 1609.4 DSRC/WAVE network layers, including multi-channel operation and QoS channel access. It employs the MiXiM suite to model transmissions as two-dimensional (time and frequency) functions of signal power that are modified by path loss and fading effects (both stochastic and deterministic, e.g., due to buildings). Frame reception is computed based on dividing these functions for signal, interference, and noise to derive the SNIR and, from that, the bit error rate. Veins also provides realistic node mobility via the SUMO[2] road traffic simulator.

[1] http://veins.car2x.org/

[2] http://sumo.sourceforge.net/

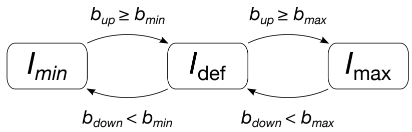


Figure 4: State diagram of a transmit rate control algorithm. The beacon interval (defined in the three states) changes according to the channel busy ratio. The transition is performed if the busy ratio is over or under a threshold for a given time interval.

5.1. Baseline Protocols

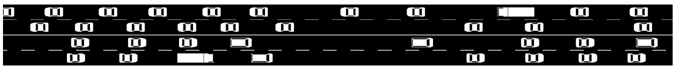
We compare our multi-channel protocol MCB in terms of reliability, channel load and performance. As a baseline, we compare MCB with ATB (introduced in Section 3.2). As an alternative, we also investigate how well a beaconing protocol performs that modulates the inter-beacon interval via a mechanism modeled after ETSI ITS-G5 Transmit Rate Control (TRC). TRC is a subset of the ETSI ITS-G5 Decentralized Congestion Control (DCC) mechanism [4] and represents a standardized transmit rate adaption algorithm which adapts the inter-packet interval according to a simple state machine consisting of independent states corresponding to different beaconing intervals.

TRC measures the channel busy ratio b_t in a periodic fashion by using a straightforward sampling process: The busy ratio b_t is defined as the fraction of probes in a defined time window of approximately 1 s length for which Clear Channel Assessment (CCA) reported the channel to be busy. Based on b_t it performs the necessary transitions in a state graph. We employ a version using three states and three beaconing intervals, shown in Figure 4. The parameters b_{up} and b_{down} are filtered busy ratios in time windows of 1 s and 5 s, respectively, to decide whether to increase or decrease the inter beacon interval. This allows the protocol to react to overloaded channels, albeit with a delay, and to eventually recover when the channel becomes less busy again.

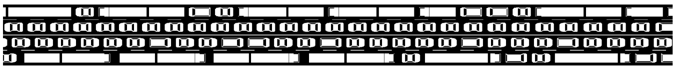
To compare MCB with a baseline multi-channel protocol, we implemented Random Channel Selector (RCS), a simple message dissemination protocol which randomly chooses a SCH to transmit payload information as well as randomly chooses a time within the CCH to announce information. The selection on what SCH to tune to is also randomly chosen, the calculation of message utility disabled.

5.2. Simulation Scenarios and Parameters

We prepare a freeway scenario with a length of 2 km having two lanes in each direction. There are two traffic flows configured starting at each end and meeting in



(a) medium vehicle density



(b) road traffic congestion

Figure 5: Two different scenarios of traffic on a freeway

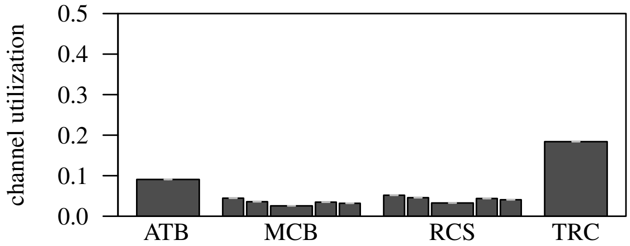
Parameter	MCB	ATB	TRC
min. beacon Interval I_{min}	100 ms		40 ms
def. beacon Interval I_{def}	-		500 ms
max. beacon Interval I_{max}	1 s		1 s
channel weighting w_{C}	2		-
interval weighting w_{I}	0.75		-
b_{min}	-		0.15
b_{max}	-		0.40
header length		88 bit	
knowledge base entry size		64 B	
max packet size		512 B	
dummy msg. interval		500 ms	
NIC bitrate		18 Mbit/s	
NIC TX power		20 mW	
path loss model		*freespace*, $\alpha = 2.0$	
# of used channels	1+4	1	1
freeway length		2 km	
traffic density (medium)		58 veh/km	
traffic density (congestion)		185 veh/km	

Table 2: Overview of Simulation Parameters

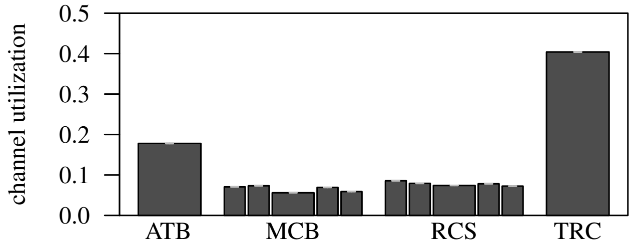
between like shown in Figure 5. We perform our simulations with two different vehicle densities, a medium utilized freeway shown in Figure 5a and a jam scenario outlined in Figure 5b where the freeway is completely filled with vehicles. We configure vehicles (90 % cars, 10 % trucks) of randomly distributed dimensions and moving according to the SUMO standard *Krauss* driver model.

Every protocol performs knowledge base management as detailed in Section 3.2.1, fed by a process generating low priority dummy messages to generate background traffic. We instrumented this mechanism such that the perceived utility of dummy messages is always lower than that of the messages we trace through the network and that utility does not decrease over time. This is necessary to keep the protocols comparable with each other, since otherwise outdated traffic information items get removed from the knowledge base.

In each simulation run, one vehicle in the middle of the freeway starts disseminating a high priority message after protocol execution has reached a steady state. Each simulation is repeatedly executed for different random number seeds for protocol operation and vehicle mobility. For statistical accuracy, we conduct 60 independent simulation runs. We record data within a region of interest of 1 km to minimize border effects. All relevant simulation parameters are summarized in Table 2.



(a) Medium traffic density



(b) Very high traffic density (traffic jam)

Figure 6: Channel utilization.

6. Results and Discussion

We concentrate on four metrics: As low level performance indicators we investigate, first, the mean channel utilization and, second, the packet success rate to get an indication of the sensitivity and efficiency of the protocol in question. Third, to get further insights into protocol behavior, we investigate the mean beaconing interval of the used dissemination protocol. Finally, we investigate the relative message dissemination speed to gauge protocol performance on an application level.

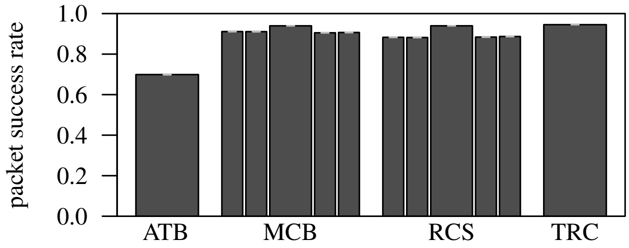
6.1. Channel Utilization

The first metric we select to investigate channel conditions is the channel utilization experienced by each individual vehicle. Similar to the well known channel busy ratio, this metric is calculated as the fraction of simulation time for which physical CCA of that vehicle would have considered the channel busy.

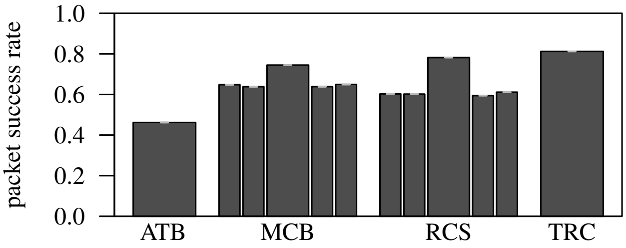
Figures 6a and 6b show the results for the medium utilized and congested freeway scenarios. We show results in the form of bar plots, plotting the mean channel utilization for each scenario along with 95 % confidence intervals. For multi-channel protocols we show the utilization separated by channel (CCH in the center, surrounded by SCHs one to four).

Aside from an increase in channel utilization across all protocols, results for the congested scenario are very much comparable to those obtained at medium vehicle density, indicating that all protocols are successful in adapting each vehicle's channel utilization to the total available capacity.

Both MCB and RCS can be seen to distribute payload transmissions evenly across all SCHs. They can also be seen to keep channel utilization very low, following their aim of not overloading the channel. Channel utilization of

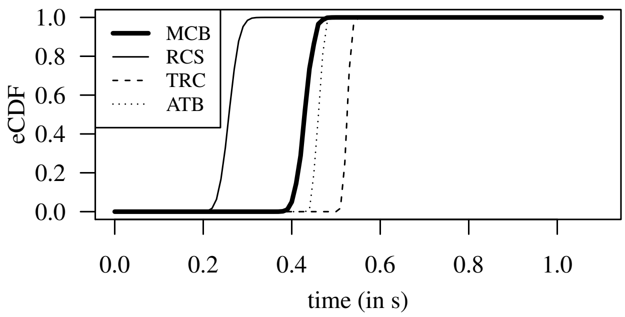


(a) Medium traffic density

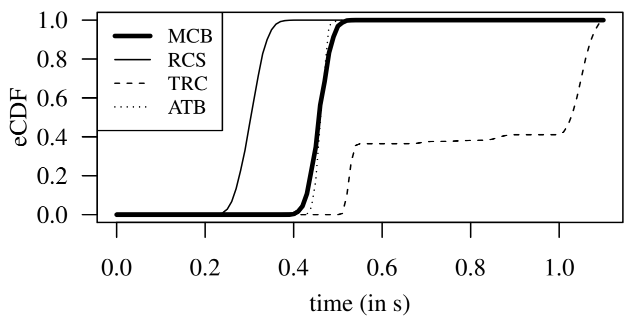


(b) Very high traffic density (traffic jam)

Figure 7: Packet success rate.



(a) Medium traffic density



(b) Very high traffic density (traffic jam)

Figure 8: Beacon interval.

ATB is higher, as it sends all data on a single channel. At the same time, however, it can use the CCH for 100 % of the time, more than doubling its available channel capacity compared to channel-switching protocols, yielding a net channel load that is roughly comparable.

TRC shows increased channel use, though still at very reasonable values: It fulfills its goal of keeping channel utilization below $b_{\max} = 0.40$ even in the jam scenario.

The impact of these different ways of utilizing the channels becomes more clear when we investigate the packet success rate.

6.2. Packet Success Rate

To calculate a packet success rate for broadcast transmission of frames, the simulation calculates each frame's reception probability twice: once using the exact SNIR value of the channel, once disregarding interference. Any frame that clears both hurdles is counted as successfully received; any frame that only clears the second one is counted as a collision. The packet success rate divides the first count by the sum of both to give an indication of what fraction of packets were lost because of collisions – or, vice versa, how much of the used channel capacity was not wasted.

We first investigate the results obtained for the medium utilized freeway, which we plot in Figure 7a. Comparing the relation between results for all four protocols, it appears that the packet success rate of MCB, RCS, and TRC is approximately equal. ATB, the predecessor of MCB, makes less efficient use of the channel. The same conclusions hold in the congested scenario (Figure 7b), though it becomes apparent that all protocols' operation is degraded by packet collisions.

6.3. Beacon Interval

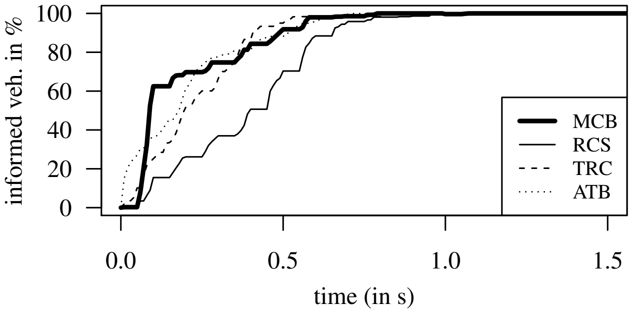
Having discussed channel utilization and efficiency, we can now turn our attention to higher layer metrics. We first discuss the distribution of the inter-beacon intervals, which are dynamically adapted by the four protocols. Figures 8a and 8b show the results in the form of an empirical Cumulative Density Function (eCDF) each, again for both the medium density and the congested scenario.

In the congested scenario plotted in Figure 8b, it is apparent that TRC chooses either of two beacon intervals. The reason is clear from looking at Figure 6b: the channel utilization indicates that the busy ratio b_t must be distributed around the second threshold $b_{\max}$.

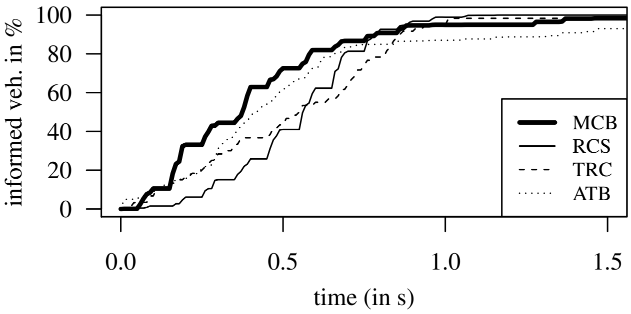
In all scenarios, ATB and MCB can choose very similar beacon intervals, corresponding to their net channel load discussed in Section 6.1. As RCS disables smart calculation of message utility, it always chooses a lower beacon interval – albeit with little benefit as can be seen when investigating an application layer metric.

6.4. Fraction of Informed Vehicles

In order to draw conclusions about the actual application layer performance of the four protocols, we track how fast a single piece of information spreads through the network. We generate such a datum in the middle of the freeway, inserting it into the knowledge base of a single vehicle, as described in Section 5.2. For each time instant in the network we then track which fraction of all vehicles already received this particular information (ignoring disseminated background traffic).



(a) Medium traffic density



(b) Very high traffic density (traffic jam)

Figure 9: Fraction of informed vehicles.

The results for the medium density and the congested scenario are plotted in Figures 9a and 9b, respectively. For each time step after the start of message dissemination (normalized to $t = 0$), we plot the mean fraction of informed vehicles in all simulation repetitions.

All the previously discussed factors (how heavily the channel is utilized, to what degree this is actually beneficial, and how fast information can be re-broadcast) influence this metric. As can be seen, the discussed effects lead to MCB propagating information substantially faster than either ATB or TRC – even though it suffers from a short time lag for announcing a beacon and switching channels. Moreover, a benefit of MCB is visible not just in the congested scenario, but it is still very visible in the medium density scenario: Even here, MCB substantially decreases the time for vehicles to be informed of new information. Only in the late phases of information dissemination, after 80 % of all vehicles have already been informed, do other protocols catch up. RCS, the baseline multi-channel protocol, performs worst: even though it managed to perfectly distribute channel load (Section 6.1), did not suffer from more packet loss (Section 6.2), and was transmitting beacons quicker (Section 6.3) its speed of information propagation lagged behind all other protocols.

7. Conclusion

We presented Multi-Channel Beacon (MCB), a novel beaconing protocol for a Single-Radio Multi-Channel (SR-MC) system that, for the first time, makes use of the multiple SCHs available in DSRC/WAVE in order to use all the available network capacity. MCB relies on careful selection of when to send coordination information. It can thus make efficient use of the additional capacity afforded by otherwise unused channels.

In the scope of a simulation study we illustrated that, by reducing channel load on the CCH compared to single channel beaconing solutions, beacons can be sent more frequently and with higher reliability. The result is that MCB is not only able to compensate for the overhead incurred by the necessary channel coordination, but that it can deliver substantially improved protocol performance compared to state of the art (that is, single-channel) beaconing protocols. Despite operating as a single radio system – and thus losing capacity to channel switching and to coordination overhead – typical scenarios allow MCB to inform twice as many vehicles in the first 100 ms.

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