Use Both Lanes: Multi-Channel Beaconing for Message Dissemination in Vehicular Networks

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***Abstract*—We study the feasibility of multi-channel beaconing for efficient data dissemination in vehicular networks. Beaconing, i.e., sending small one-hop broadcasts in a periodic fashion, is now a state of the art method for information dissemination in vehicular networks. The main research challenge is to minimize the communication delay while efficiently using the wireless medium without ever overloading the wireless channel. Currently, several approaches to meet these demands can be identified, but they all share the disadvantage of using only a single wireless channel. This is a major bottleneck at high vehicle densities, leading to high delays or packet loss. In this work, we investigate the potentials of a multi-channel approach by extending the delay sensitive and congestion aware Adaptive Traffic Beacon (ATB) protocol to make full use of IEEE 802.11p/1609.4 DSRC/WAVE. We present a novel channel scheduling algorithm and incorporate it into an improved information dissemination protocol. We evaluate our approach in simulations, employing the extended protocol to allow vehicles to dynamically adapt their route to changing traffic conditions. We are able to demonstrate the feasibility of this multi-channel approach, showing that it successfully reduces the channel utilization and observed packet collisions without sacrificing the goodput.**

I. 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 Dedicated Short Range Communication (DSRC), leading to industry standards IEEE 802.11p / IEEE 1609.4 [2], [3] that define both the physical and the access layer for Inter-Vehicle Communication (IVC). 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) [4] and Basic Safety Messages (BSMs) [5], and are now thought to be the main communication primitive for a wide range of IVC applications. These applications can be separated into three categories, namely safety, efficiency, and comfort, each having different demands in terms of delay, data rates, and reliability.

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 beacon interval has been identified as the most critical parameter to adapt [6]–[10]. Besides this transmit rate control, ETSI ITS-G5 furthermore considers transmit power control and even more complex concepts for channel access, whereas most other approaches very successfully focus on adaptive beaconing times only. The main objective is to minimize the communication delay while keeping the wireless channel use well below its capacity to avoid packet collisions. The presented concepts for adaptive beaconing rely on a single wireless channel making use of either the IEEE 1609.4 control or one of the service channels.

In this paper, we study the feasibility of using multiple channels at the same time. In particular, we extend the delay sensitive and congestion aware Adaptive Traffic Beacon (ATB) protocol to be used in a multi-channel fashion. We present a novel concept for channel scheduling, which substantially reduces the channel utilization and observed packet collisions without sacrificing the goodput, while at the same time increasing reliability. 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 multi-channel is not only feasible but also leads to substantial performance improvements.

Our main contributions can be summarized as follows:

- To the best of our knowledge, we are the first to study the feasibility of using multi-channel systems for beaconing based information dissemination in vehicular networks.
- We study possible channel scheduling strategies and demonstrate the advantages of multi-channel systems.
- Using a traffic information system as an example, we clearly show that the use of multiple channels not only reduces the load of the wireless channel(s) but also enables low latency information dissemination as required for safety applications.

II. 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. The usage of CAMs [4] and BSMs [5] 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.

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SOTIS [11] 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 [12], 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.

ATB [6] extends this approach by proposing a novel prioritization scheme, where the beacon 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 [7].

FairDD [13] 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 [14] 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 Single-Radio Multi-Channel (SR-MC) and Multi-Radio Multi-Channel (MR-MC) systems have been described in [15]. The difference of the physical and the hop count interference model, and how this affects the complexity of channel assignment in a wireless mesh network, has been studied in [16]. The question of how the capacity of such a network scales with increasing number of nodes has been studied in [17].

Recently, the IEEE 802.11p / IEEE 1609 DSRC/WAVE series of standards [2] was developed, which provides a comprehensive communication stack for IVC. The IEEE 1609.4 standard [18] provides multi-channel operation employing a split-phase channel switching approach with seven and five channels in the U.S. and Europe, respectively. Basically, WAVE operates on top of the IEEE 802.11p [3] physical and MAC layers to add a fully-featured communication stack.

It is this stack our work builds on.

III. Problem Formulation

Our goal is to combine the beaconing techniques of ATB (we discuss the principles of ATB in more detail in Section IV) with the multi-channel operation of WAVE as specified in the current standard. According to [18, section 5.3.1], the channel selection scheme is left open to the application developer, as (of course) is the selection of time and content of a transmission. In this paper, we aim to answer the challenging question of *when* to transmit on *which* channel.

We surveyed multi-channel scheduling approaches for single-radio and multi-radio networks, which try to mitigate SR-MC problems like deafness, channel deadlock, multi-channel broadcast, and split network problems. We found that dedicated control channel approaches are not suitable to solve these problems in the context of IVC and that channel hopping incurs undue control overhead. IEEE 1609.4 itself is a split phase protocol, so we developed our own channel selection strategy on top of it.

We address the aforementioned classical scheduling problem by proposing algorithms for sending and receiving nodes to tune their radio to a suitable channel to minimize packet collisions without sacrificing information dissemination speed.

IV. The Basic ATB Protocol

The original single-channel ATB protocol, which we base our work on, consists of several parts [6]. 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.

A. 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 air frame and sends them (i.e., the most important ones) as a broadcast 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 air 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 [14]. 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 [6]. Accordingly, each knowledge base entry contains the type of event (e.g., *accident*), timestamp, location, priority, and an identifier of the affected road.

B. 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 [14], to the straightforward calculation presented in [6] used in this evaluation, which considers solely the age of an entry and current proximity to the event origin.

In every case, however, 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 $[I_{\text{min}}, I_{\text{max}}]$, the recommended beacon interval ΔI is calculated according to [6] as follows.

$$I = (1 - w_I) \times P^2 + w_I \times C^2 \tag{1}$$

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

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. Packet collisions 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 of a predefined period of time can be measured.

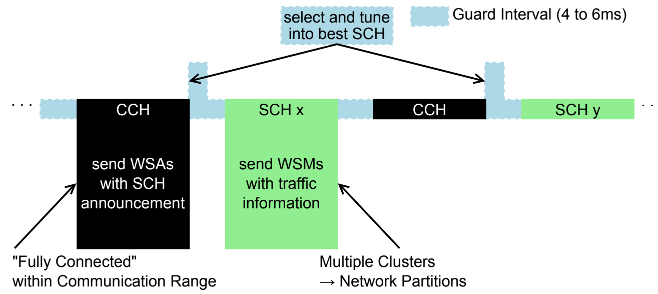


Fig. 1. ATB-MCH example Behavior: During the CCH interval all vehicles share a single channel, while during the SCH interval they communicate in clusters.

V. The ATB-MCH Extension

In the following, we outline the system architecture of ATB-MCH, which extends ATB to provide single-radio multi-channel message dissemination. Unlike the original ATB specification, ATB-MCH is designed to operate on the physical and MAC layers of IEEE 802.11p. Additionally, IEEE 1609.4 on top of the MAC layer provides channel switching.

We define a new message type based on WAVE Service Announcements (WSAs), which announces an upcoming beacon and its corresponding Service Channel (SCH) during the Control Channel (CCH) period. To effectively utilize all available channels, we employ a scheduling approach which allows both a sender to determine on which SCH to transmit what information – and a receiver to determine which SCH to tune to in order to obtain the most important information, leading to a split phase scheduling approach and the channel dynamics illustrated in Figure 1.

In the following we present the individual building blocks of ATB-MCH. The interoperation of these building blocks is illustrated in the state diagram of Figure 2.

A. Sender Channel Selection Strategy

The simplest approach for a sender to select the SCHs for transmission is to evenly distribute all packets over all available SCHs. This might be a good idea if (1) all nodes use static beaconing and (2) node topologies are stable. The last prerequisite arises from the fact that the SCHs would be utilized non uniformly if the node density changes too frequently. Since for typical IVC scenarios neither (1) nor (2) holds, a better scheduling approach is necessary.

Looking at how ATB calculates the beaconing interval, a sophisticated channel utilization metric is already available. The next step is to take into account the current utilization of each SCH and to then select the best fitting channel to transmit the traffic information packet.

Furthermore, the amount of advertised traffic information packets in the current CCH interval for the next SCH phase should be taken into account for the selection of the most suitable next SCH.

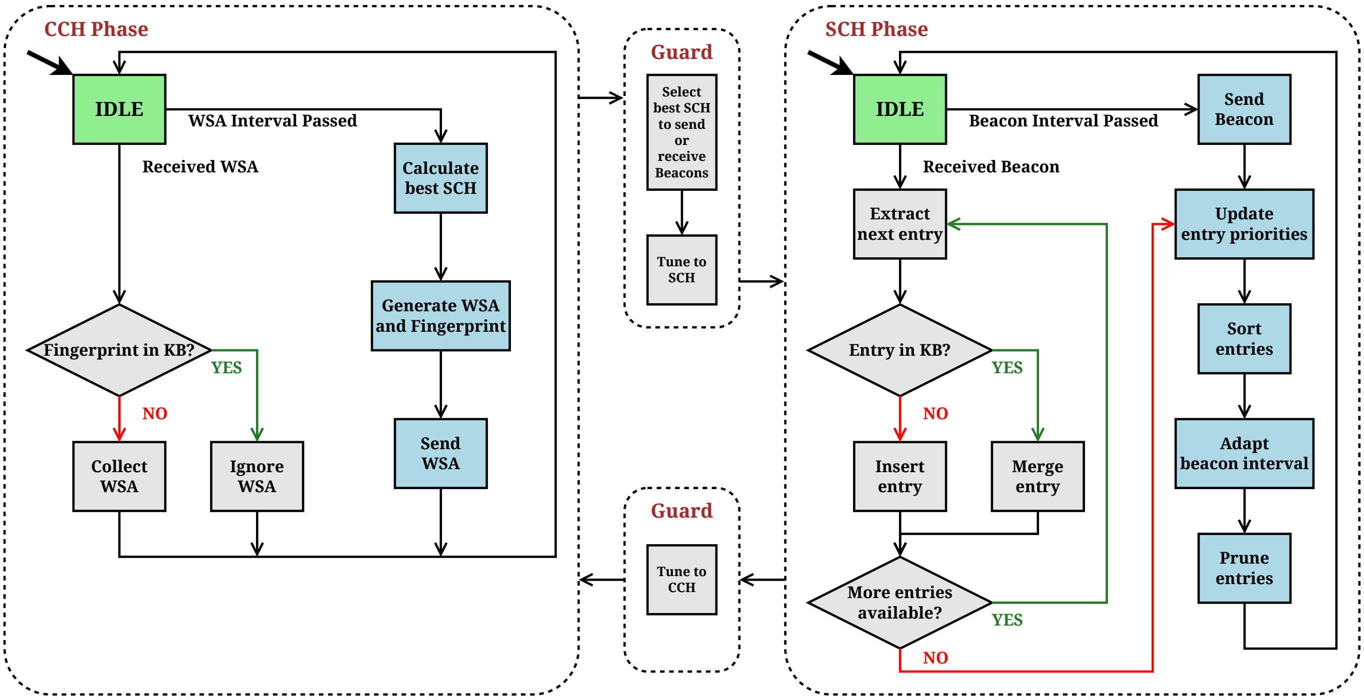


Fig. 2. ATB-MCH state diagram: After each reception of a WSA the fingerprinting technique checks whether the information is already in the knowledge base. If so, the WSA is discarded; if not, the WSA is collected. In the guard interval of the SCH, the best fitting SCH is selected according to the receivers channel selection strategy by evaluating all collected WSAs. Afterwards the radio is tuned to the new SCH and the beacons carrying the traffic information are exchanged.

Combining all these parameters, the proposed multi-channel scheduling algorithm for the sender can be described as a three step process:

step 1: Find the SCH with the lowest encountered packet collisions in the past;

step 2: Determine the SCH with the best channel quality (as defined in Section IV-B) from all available SCHs;

step 3: Select the SCH from either step 1 or step 2, whichever has fewer beacon announcements in the current CCH interval.

With this metric the best fitting channels (according to utilization values in the present and past) are determined, and from those the SCH with fewest announced beacons is selected. Thus, no maximum threshold for WSAs is necessary, i.e., defining an amount of WSAs for which a SCH selection is acceptable.

For sending a WSA and the later WAVE Short Message (WSM) containing the traffic information, some delay has to be added. This need arises from the fact that the application layer is not aware which phase (either the CCH or the SCHs phase) is currently active.

If, at the time of sending both packets down to the MAC layer, one of the SCHs were active, the WSM would get transmitted immediately (assuming empty queues and a free channel) whereas the WSA would get queued until the CCH is active. Thus, a receiver would be unaware of the announcement and miss the packet with a high probability. Conversely, the receiver might tune to the SCH announced in the upcoming WSA, while the referenced beacon was already sent in the past interval. This causes the receiver to gain no new information and to possibly miss important traffic information packets from other nodes. To overcome this problem, the WSA and the WSM are handed to the MAC layer with a relative delay of 50 ms.

B. Receiver Channel Selection Strategy

The purpose of the receivers' channel scheduling is to determine the best SCH to tune to (during the corresponding phase). The simplest approach would be to take either the first, the last, or indeed an arbitrary WSA and tune to the advertised SCH in the next interval. As the information sent by neighboring nodes is not of equal utility, however, some WSAs will be more useful to a receiver than others.

Another approach for selecting the right SCH is to count all received WSAs and to switch to the SCH which is announced the most often. This might allow catching most transmitted packets, although the chance for packet collisions is higher.

Introducing priority mechanisms, one could also select the SCH which gets announced by the highest priority messages. Consider that each WSA contains a priority field, onto which we map the interval $[0, 1]$, with lower values denoting more important messages. Given

$$\omega_i = \frac{\sum \text{priority of WSAs for SCH}_i}{\#\text{ announcements of SCH}_i} \tag{3}$$

this allows a receiver to deduce that a SCH is likely to contain more important information when its ω_i is lower. The channel with the lowest value of ω_i is then switched to in the next SCH interval. ATB-MCH adopts this approach: WSAs are collected during each CCH interval and the best fitting SCH is selected within the guard interval.

The prioritization mechanism for traffic information messages in ATB-MCH involves two mechanisms. First, a WSA packet consists of a field denoting the priority of the information which is announced. Here, the message utility (cf. Section IV-A) of the first element in the knowledge base is used.

Secondly, to support Quality of Service (QoS) among different beacons, the message priority of the whole beacon also defines the assignment of one of the (at most) four available Access Categories (ACs) provided by the IEEE 802.11e Enhanced Distributed Channel Access (EDCA) mechanism. The AC determines in EDCA parameters and, thus, into which MAC queue to put the packet and how to handle prioritization for channel access. Since ATB already calculates priorities based on the current channel conditions as well as on the importance of the payload data, this message priority value can simply be mapped to the different ACs in a straightforward fashion: AC_VO, AC_VI, AC_BE are assigned to message priorities in intervals $\big[0.00, 0.33\big]$, $\big(0.33, 0.66\big]$, $\big(0.66, 1.00\big]$, respectively. The lowest priority traffic queue AC_BK is kept free for future use, e.g., to support IP traffic.

C. Fingerprinting Technique

Another feature investigated in the context of ATB-MCH is a fingerprinting technique. Its main purpose is to prevent the receiver of a WSA from switching to an announced SCH when the advertised beacon contains no new information, i.e., the information is already stored in the local knowledge base.

This technique embeds a fingerprint of the topmost knowledge base entry in each WSA, e.g., in the application defined part. The fingerprint (which can take the form of a fitting hash value) contains the kind of information as well as the affected road and lane.

On the receiving side the fingerprint is compared with the contents of the local knowledge base. If a match is found, the whole WSA is discarded and not included in the calculation of the best fitting receiving channel to tune to.

The following example might serve to illustrate the benefit of this technique. If an incident happens on a busy intersection, many vehicles will be affected and, thus, start disseminating (identical) notifications about this event. With the presented fingerprinting technique, the tuning to a SCH containing (as the most important information) a notification about the accident when it is already present in the local knowledge base is avoided, allowing vehicles to receive other useful information that might be transmitted on different SCHs.

VI. Performance Evaluation

In this section, we first investigate the theoretic performance gain of an idealized extension of ATB to multi-channel; we then investigate the real gain of the developed multi-channel extension ATB-MCH compared to a single-channel approach. We detail the used scenarios, the configured simulation parameters,

Fig. 3. Scenario modeling the municipality of *Breitenbach am Inn/Tirol*, as imported from OpenStreetMap. A single traffic flow starts from *Ried* (top right corner) and is heading to *Dorf* (bottom left corner). An artificial accident is introduced at a fixed point in time. ATB enables vehicles to calculate and take detours as necessary.

and the gathered statistics. We concentrate on three metrics to draw conclusions about the impact of information dissemination on channel conditions: the observed packet collisions, the channel utilization, and the mean beaconing interval. For the channel utilization the ratio between the whole simulation time and the time receiving nodes indicate a busy channel is calculated; for better comparability, this ratio is given relative to the maximum measured utilization for both the original ATB version and IEEE 802.11p based versions. For the simulation experiments, we used the Veins[1] simulation framework [19], which provides realistic node mobility via the SUMO[2] road traffic simulator, a fully-featured IEEE 802.11p and IEEE 1609.4 simulation model [20] as well as the MiXiM physical layer model.

A. Simulation Scenarios and Parameters

We prepared three different scenarios: an artificial one with a simple detour, as well as a freeway and a rural area in the municipality of *Breitenbach am Inn/Tirol*, both imported from OpenStreetMap. For brevity we report in this paper only the results obtained in the *Breitenbach* scenario, but note that each of the presented effects occurred in all three scenarios.

The Breitenbach scenario is shown in Figure 3: one traffic flow is configured which starts on the right top corner called *Ried* and ends on the opposite bottom corner named *Dorf*, one vehicle departing every five seconds. The road network has two lanes on the selected route, allowing the vehicles to overtake each other if necessary.

An artificial accident is introduced at a fixed point in time: a vehicle stops for a given duration and broadcasts a warning message. This warning message, transmitted using ATB or ATB-MCH, respectively, allows other vehicles to calculate and

[1] http://veins.car2x.org/
[2] http://sumo.sourceforge.net/

TABLE I
OVERVIEW OF SIMULATION PARAMETERS

Parameter	ATB vs. ATB$^+$	ATB-MCH$^-$ vs. ATB-MCH
min. beacon Interval $I_{\min}$	30 ms	30 ms
max. beacon Interval $I_{\max}$	1 s	1 s
channel weighting w_C	2	2
interval weighting w_I	0.75	0.75
NIC bitrate	2 Mbit/s	18 Mbit/s
NIC TXPower	110.11 mW	20 mW
simulated time	500 s	500 s
repetitions	5	3
vehicle mobility model	Krauss	Krauss
max. acceleration	$2.6\,\mathrm{m/s^2}$	$2.6\,\mathrm{m/s^2}$
driver imperfection σ	0.5	0.5
max. deceleration	$4.5\,\mathrm{m/s^2}$	$4.5\,\mathrm{m/s^2}$
vehicle length	2.5 m	2.5 m
min. gap	2.5 m	2.5 m
number of accidents	1	1
accident start	40 s	40 s
accident duration	60 s	60 s

take detours if necessary. This, in turn, causes traffic conditions on the detours to quickly deteriorate, which requires further re-routing of vehicles, and thus leads to highly dynamic network and road traffic behavior.

A summary of the relevant simulation parameters is given in Table I. We configured vehicles in SUMO to use the default parameter set, representing average automobiles. The same holds for nodes' network cards which were configured to default values. To ensure statistical relevance of the measurements, we used three and five runs of differing vehicular mobility patterns.

For the minimum and maximum beacon interval of ATB-MCH we configured 30 ms and 1 s, respectively. The maximum beaconing interval is designed to enforce rapid information dissemination. Although the minimum beaconing interval is below 100 ms, which means that it could be possible that a node transmits within the same sync-interval two beacons, the observed mean beaconing rate is in the range of a few hundred milliseconds.

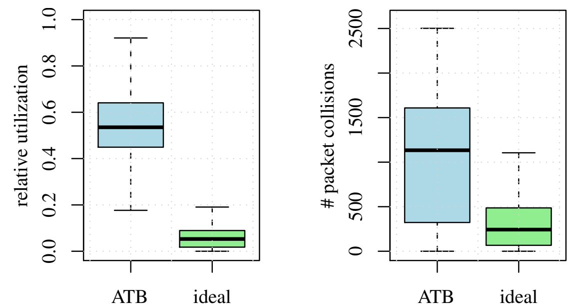
B. Upper Bound of Performance Gain

To serve as a theoretic upper bound of performance gain for a straightforward extension of ATB to multi-channel use, we extended it by emulating an ideal radio, which allows simultaneous communication on all available channels. The used radio is adapted from IEEE 802.11b, thus, the available channels range from 1 to 13. All simulation parameters are kept equal (scenario *ATB vs. ATB*$^+$ in Table I).

For each beacon transmission, the sending node picks a new channel from the set of m of available channels in a round robin fashion as follows.

$$c_{i+1} = \big(c_i \bmod (m-1)\big) + 1 \quad (4)$$

1) Channel Utilization: We plot the channel utilization, aggregated over all channels, in Figure 4a in the form of a box plot. As can be seen, the channel utilization differs greatly



(a) Channel Utilization

(b) Number of Packet Collisions

Fig. 4. Channel utilization and number of observed packet collisions for an idealized multi-channel version.

between ATB and the idealized multi-channel version. It can be concluded that the channel is about ten times more utilized than in the multi-channel version looking at the distribution of both medians.

2) Observed Packet Collisions: Comparing the observed packet collisions of ATB with the idealized multi-channel version in Figure 4b we notice a substantial difference: ATB causes more than four times as many collisions.

Although the improvement is quite high, it does not scale well since the multi-channel version has 13 (the number of channels) times more available resources.

C. Benefit of Multiple Channels

To point out the impact of the use of more than one channel for disseminating information, we compare ATB-MCH with a single channel version that only uses the CCH. When the radio is tuned to a SCH, any potential beacon sent down to the MAC layer gets queued until the next CCH period. All simulation parameters are kept equal (scenario *ATB-MCH*$^-$ *vs. ATB-MCH* in Table I). We collected the following statistics:

1) Channel Utilization: The channel utilizations of the single-channel and the multi-channel approach are comparable, as seen in Figure 5a. However, in the multi-channel version the usage of the CCH is slightly lower, leaving room for more packets.

2) Observed Packet Collisions: The advantages of the developed multi-channel version present themselves even more clearly when measuring the packet collisions. In Figure 5b, a clear difference of the observed packet collisions among the single-channel version and the CCH of the multi-channel version can be seen. Comparing both results, we notice that the multi-channel version exhibits only 40 % of the collisions on the CCH. Even summing up the collisions on CCH and all SCHs, the multi-channel version shows only 60 % of the collisions compared to the single-channel approach.

3) Mean Beacon Interval: The improvement of packet collisions is not due to a reduced beacon interval, as we illustrate in Figure 5c. In fact, the beacon interval is slightly reduced and shows substantially less extreme values. Furthermore, we measured an even bigger impact in the freeway scenario (results not shown), owing to the higher vehicle density.

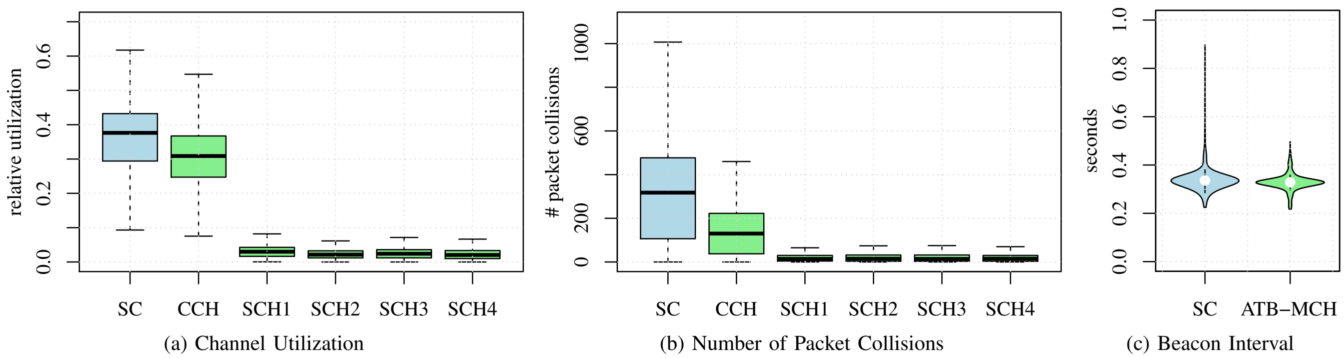


Fig. 5. Benefit of ATB-MCH (plotted as *CCH* and *SCHi*) compared to a single channel approach (labeled *SC*): both the channel utilization and the packet collisions are substantially reduced; at the same time, the beacon interval remains low.

D. Benefit of Fingerprinting

ATB-MCH fully supports multi-channel operation, where two functions were added to improve the performance. First of all, the EDCA prioritization technique, and secondly, the newly created fingerprinting technique, which is only available in multi-channel operation.

The channel utilization diagrams shown in Figure 6a clearly illustrate the impact on the SCHs load when fingerprinting is enabled. This way, all SCHs get used evenly. Otherwise, some arbitrary SCH gets preferred among the others. This can be explained as follows: When a vehicle announces a beacon with high priority on some channel like SCH_2, a node without fingerprinting must tune to this channel to receive this high priority message. After reception, the node will rebroadcast this priority beacon leading to the observed uneven utilization.

On the other hand, with enabled fingerprinting, the most important information is piggybacked onto the WSA which gets compared by the receiving node to check whether it is already included in its local knowledge base. If the information is already known, the announcement is discarded. Thus, a flood of important traffic messages does not influence the channel switching metric.

E. Benefit of EDCA

The number of packet collisions is greatly affected by the use of different contention windows and Arbitration Interframe Spaces (AIFSs) of each AC as defined by EDCA. This effect can be seen in Figure 6b. Comparing the medians, the version without enabled EDCA suffers from 1.5 times more packet collisions than with enabled EDCA on the CCH.

F. Lessons learned

To conclude the evaluation, it can be said that the ATB-MCH extension yields much benefit in terms of limited packet collisions and lower channel load on the evaluated scenarios.

The load of the CCH is drastically reduced by using the remaining four SCHs for sending traffic information. With the EDCA functionality, synchronized packet collisions on the start of a CCH phase can be avoided.

Furthermore, with our fingerprinting mechanism, initially observed problems with floods of WSAs for different SCHs containing already disseminated information are avoided. Since the packet collision rate and channel utilization is improved – and since the mean beaconing interval is not increased – we can conclude that ATB-MCH is able to use the channel more efficiently.

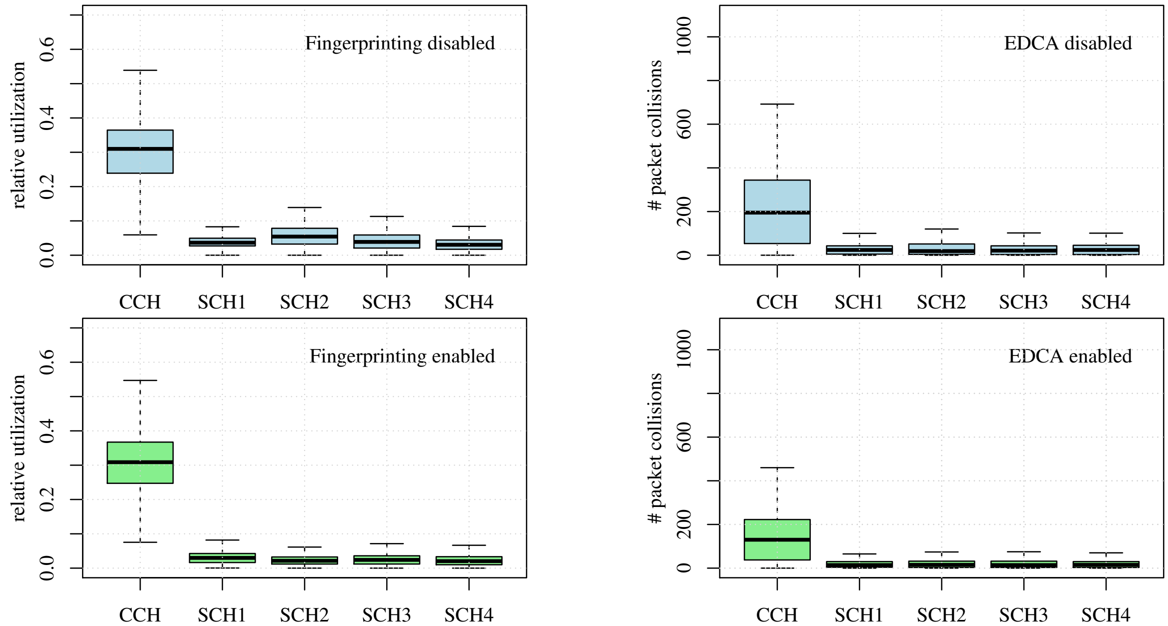
On the other hand, it has to be mentioned that using the CCH for all beacon announcements limits scalability, which is an inherent problem of such a WSA based approach. Forcing the usage of as many radios as channels would obviously avoid channel switching altogether and therefore use all wireless resources in a much more efficient way. An upper bound to this is demonstrated in a first approach of ATB where multi-channel operation is emulated by using radios which can receive on multiple channels simultaneously.

Furthermore, with EDCA a prioritization mechanism on MAC layer level is available. As only three of four priorities are used, leaving the least important one free for later use, allows the usage of other IVC related applications (e.g., entertainment applications) on the dedicated frequency band and therefore minimizing the performance impact in case of packet collisions.

VII. Conclusion and Future Work

In this work, we investigated possible multi-channel approaches for adaptive beaconing in vehicular networks. In a first step, we have shown the theoretical performance increase by emulating multi-channel operation using IEEE 802.11b. In particular, our simulations show a decrease of packet collisions by a factor of 4.6. We then investigated a true multi-channel version of ATB taking advantage of IEEE 1609.4 for realistic multi-channel operation in IEEE 802.11p based networks.

To the best of our knowledge, we are the first to study the feasibility of using multi-channel systems for beaconing based information dissemination in vehicular networks. Our simulation experiments clearly indicate that such an approach is feasible: the developed ATB-MCH is able to use the channel more efficiently: the packet collision rate and channel utilization are improved, while the mean beaconing interval is not increased. In conclusion, it can be said that this work paves the way towards a new era of multi-channel approaches for beaconing based IVC.



(a) Benefit of Fingerprinting

(b) Benefit of EDCA

Fig. 6. Benefit of the fingerprinting mechanism and EDCA in terms of channel utilization and packet collisions: fingerprinting leads to an even distribution of SCH usage, EDCA further reduces packet collisions.

In future work, we aim to research strategies to improve the performance of ATB-MCH, e.g., in the following special case. Since the minimum beacon interval configured in ATB is lower than one sync interval of WAVE (100 ms, for example 30 ms), it could happen that in one SCH interval two beacons are scheduled to be transmitted by a node. With the current architecture of ATB-MCH, the channel selection strategy for the sender could assign two different SCHs to the beacons, but only one could be transmitted in the next SCH interval on the correct channel.

References

[1] M. Gerla and L. Kleinrock, "Vehicular networks and the future of the mobile internet," *Computer Networks*, vol. 55, no. 2, February 2011.

[2] R. A. Uzcátegui and G. Acosta-Marum, "WAVE: A Tutorial," *IEEE Communications Magazine*, vol. 47, no. 5, May 2009.

[3] "Wireless Access in Vehicular Environments," IEEE, Std 802.11p-2010, July 2010.

[4] "Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 2: Specification of Cooperative Awareness Basic Service," ETSI, TS 102 637-2 V1.1.1, April 2010.

[5] SAE Int. DSRC Committee, "DSRC Message Communication Minimum Performance Requirements: Basic Safety Message for Vehicle Safety Applications," SAE, Draft Std. J2945.1 Revision 2.2, April 2011.

[6] C. Sommer, O. K. Tonguz, and F. Dressler, "Traffic Information Systems: Efficient Message Dissemination via Adaptive Beaconing," *IEEE Communications Magazine*, vol. 49, no. 5, May 2011.

[7] European Telecommunications Standards Institute, "Intelligent Transport Systems (ITS); DCC Mechanisms for ITS operating in the 5 GHz range; Access layer part," ETSI, TS 102 687 V1.1.1, July 2011.

[8] R. K. Schmidt, T. Leinmüller, E. Schoch, F. Kargl, and G. Schäfer, "Exploration of adaptive beaconing for efficient intervehicle safety communication," *IEEE Network Magazine*, vol. 24, no. 1, January 2010.

[9] M. van Eenennaam, W. Wolterink, G. Karagiannis, and G. Heijenk, "Exploring the solution space of beaconing in VANETs," in *1st IEEE Vehicular Networking Conference (VNC 2009)*. Tokyo, Japan: IEEE, October 2009.

[10] C. Sommer, S. Joerer, M. Segata, O. K. Tonguz, R. Lo Cigno, and F. Dressler, "How Shadowing Hurts Vehicular Communications and How Dynamic Beaconing Can Help," in *32nd IEEE Conference on Computer Communications (INFOCOM 2013), Mini-Conference*. Turin, Italy: IEEE, April 2013, to appear.

[11] L. Wischhof, A. Ebner, H. Rohling, M. Lott, and R. Halfmann, "SOTIS - A Self-Organizing Traffic Information System," in *57th IEEE Vehicular Technology Conference (VTC2003-Spring)*, Jeju, South Korea, April 2003.

[12] E. Van de Velde and C. Blondia, "Adaptive REACT protocol for Emergency Applications in Vehicular Networks," in *32nd IEEE Conference on Local Computer Networks (LCN 2007)*. Dublin, Ireland: IEEE, October 2007.

[13] R. S. Schwartz, A. E. Ohazulike, and H. Scholten, "Achieving Data Utility Fairness in Periodic Dissemination for VANETs," in *75st IEEE Vehicular Technology Conference (VTC2012-Spring)*. Yokohama, Japan: IEEE, May 2012.

[14] R. S. Schwartz, A. E. Ohazulike, C. Sommer, H. Scholten, F. Dressler, and P. Havinga, "Fair and Adaptive Data Dissemination for Traffic Information Systems," in *4th IEEE Vehicular Networking Conference (VNC 2012)*. Seoul, Korea: IEEE, November 2012.

[15] J. Crichigno, M.-Y. Wu, and W. Shu, "Protocols and architectures for channel assignment in wireless mesh networks," *Elsevier Ad Hoc Networks*, vol. 6, no. 7, 2008.

[16] W. Cheng, X. Cheng, T. Znati, X. Lu, and Z. Lu, "The Complexity of Channel Scheduling in Multi-Radio Multi-Channel Wireless Networks," in *28th IEEE Conference on Computer Communications (INFOCOM 2009)*, Rio de Janeiro, Brazil, April 2009.

[17] P. Kyasanur and N. H. Vaidya, "Capacity of Multi-Channel Wireless Networks: Impact of Number of Channels and Interfaces," in *11th ACM International Conference on Mobile Computing and Networking (MobiCom 2005)*. Cologne, Germany: ACM, August 2005.

[18] "IEEE Trial-Use Standard for Wireless Access in Vehicular Environments (WAVE) - Multi-channel Operation," IEEE, Std 1609.4, February 2011.

[19] C. Sommer, R. German, and F. Dressler, "Bidirectionally Coupled Network and Road Traffic Simulation for Improved IVC Analysis," *IEEE Transactions on Mobile Computing*, vol. 10, no. 1, January 2011.

[20] D. Eckhoff, C. Sommer, and F. Dressler, "On the Necessity of Accurate IEEE 802.11p Models for IVC Protocol Simulation," in *75th IEEE Vehicular Technology Conference (VTC2012-Spring)*. Yokohama, Japan: IEEE, May 2012.