A Comparison of Single- and Multi-hop Beaconing in VANETs

Jens Mittag* Florian Thomas Jérôme Härri* Hannes Hartenstein

Institute of Telematics
University of Karlsruhe, Germany
jens.mittag@kit.edu, florian.thomas@ira.uka.de,
jerome.haerri@kit.edu, hannes.hartenstein@kit.edu

ABSTRACT

Optimizing vehicular communication strategies is important for an efficient usage of the available wireless bandwidth and also critical for the success of VANETs. In this paper we address the fundamental and practical question whether the load on the wireless channel can be reduced if periodic beacon messages are transmitted over multiple hops with reduced transmit power instead of being transmitted over one hop with high transmit power. In particular, we look at the possible bandwidth savings that can be achieved by piggybacking forwarded messages into the own next beacon transmission. For that matter, we first propose an analytical model to compute a lower bound for the resulting channel load when single- or multi-hop dissemination of beacons is performed. In this model we assume optimal channel conditions and perfect relaying and piggybacking decisions to show that a reduction of the load by multi-hop is possible and intrinsically related to piggybacking. Further, we show that the possible savings depend on the ratio between the size of the header and the payload of a beacon and that a reduction of the load is theoretically possible if the header is larger than the payload — what would be the case in VANETs if security overheads are considered part of the header. We then perform a simulative comparison of single- and multi-hop beaconing to evaluate the impact of effects such as packet collisions and channel fading. We show that the possible savings are difficult to exploit imperfect channel conditions and relaying decisions.

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

General Terms: Design, Performance.

Keywords: Analysis, Multi-Hop, VANETs.

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1. INTRODUCTION

Beaconing, or the process of periodically and locally broadcasting status information, is a key communication pattern in Vehicular Ad-hoc Networks (VANETs). Vehicles equipped with communication devices use this process to obtain information related to other communicating partners and thus to other vehicles. Beacon messages contain a vehicle's identifier, its geographical position and possibly its velocity. The process of beaconing therefore provides a vehicle's awareness of its surrounding.

Considering VANET applications for traffic safety or efficiency, this vehicular awareness must be made available to guarantee the correct evaluation of safety-related situations or to assess the congestion level on traffic ways. This information may also be used as a major input parameter to automated driving applications. Considering that driving decisions might be made based on information from beacon messages, beaconing may be considered as mission critical.

Beacon messages must be received up to a certain distance with a specific freshness in order to be useful to VANET applications. The precise distance or freshness is determined by a VANET application and based on the objectives and demands of such applications. Specifying a specific distance or freshness is out of scope of this paper. Instead we focus on finding appropriate ways to deliver beacons to the intended recipients, which can be seen as a dissemination problem.

Beaconing yet represents a communication challenge for data dissemination considering that *all* communication partners must transmit data generated at a potentially high rate[1]. Such aspect typically tends to increase the load on the wireless channel which in turn reduces the performance of the global communication system and challenges a reliable and successful delivery.

The communication layer may opt for two options to broadcast these beacons. It can either use a high transmit power to reach the required dissemination distance in one hop or use a small transmit power and cover the same distance by means of multi-hop relaying. Both approaches have advantages and disadvantages and usually depend on the particularities of the environment and the relaying scheme. Nevertheless, a fundamental question is: which approach requires less network resources in terms of a lower channel load?

In [1], Tavli showed that in general multi-hop broadcasting is not better than single hop broadcasting considering

[1]Intellidrive (formerly VII) and the CAR 2 CAR Communication Consortium recommend for instance a 10Hz beaconing rate.

independent relaying transmissions. Yet, unlike single-hop, multi-hop beaconing is in practice subject to intelligent relaying strategies and its efficiency depends on the applied optimization mechanisms, an aspect not covered by Tavli's study. One optimization for instance could be the multiplexing of multiple beacon messages into one single transmission. By piggybacking one or several (to be forwarded) messages into the next own beacon transmission, a node could save the overhead of multiple message headers and thereby reduce the load which is put on the channel. Particularly in VANETs, where beacon signatures that are added due to security requirements could be considered as part of the header, such savings might be significant. Therefore, would it be possible to have a different conclusion that from Tavli's by employing an intelligent multiplexing scheme at each relaying node?

From an information's quality perspective, the obvious advantages of single-hop beaconing are a direct vehicle-to-vehicle communication in the area of interest and a low latency due to the lack of intermediaries. Considering the mission critical aspect of this process, a first hand information at low latency might be significantly more important than the potential cost to obtain it. Therefore, when studying intelligent relaying strategies, not only the impact on the channel load but also the information's quality should be considered.

In this paper, we compare single- to multi-hop beacon dissemination and provide an answer to the fundamental and practical question whether multi-hop beaconing with intelligent message multiplexing is able to reduce the load on the wireless channel. We notably present the following contributions:

- We provide a framework to compare the conceptually different approaches of single-hop and multi-hop beaconing considering both channel load and information quality.
- We analyze the fundamental issues of multi-hop beacon dissemination and develop an analytical model for the computation of the channel capacity that is required to cover an intended dissemination area by either one or several hops. In our analysis, we assume an ideal environment and optimal relaying decisions.
- We identify the influencing factors which determine the outcome of the comparison and discuss their possible impacts.
- We perform simulations to include effects such as packet collisions, fast-fading channel conditions and non-perfect relaying decisions.
- We show that multi-hop beaconing is in general not able to provide a better neighborhood awareness than single-hop beaconing.

The rest of the paper is organized as follows. Section 2 provides an overview about related work, while Section 3 describes our comparison methodology. In Section 4, we develop and discuss our analytical model for the computation of channel loads in optimal environments, followed by a simulative evaluation in Section 5 where we consider an increased degree of realism, i.e. packet collissions, channel fading and non-optimal behavior of the dissemination protocol. Finally, Section 6 concludes the paper and highlights the impacts of our study.

2. RELATED WORK

Single-hop vs. multi-hop communication has been a popular investigation topic in infrastructure-based wireless networks. Considering a desired fixed data rate and a base-station centric cell as coverage area, the required signal-to-noise ratio (SNR) at a mobile terminal is expected to be harder to obtain with an increasing distance between base station and mobile terminal. The typical solution to overcome this limitation is usually to shrink the cells' size. Considering that it usually implies deploying significantly more base stations, allowing terminals to relay packets has been seen as an interesting alternative. Studies such as [2, 3, 4, 5] notably justified this idea by showing that multi-hop communication in wireless networks could significantly improve the throughput and network capacity.

Studies in WiMAX also recently addressed this aspect to overcome capacity, QoS and coverage limitations at a reduced cost. The new IEEE 802.16j draft, the Mobile Multi-hop Relay (MMR) specification for IEEE 802.16, specifically investigates the benefits that could be obtained by designing specific WiMAX mobile stations as relays with adapted transmit power to their pico-cells. Recent studies showed positive results in multi-hop for WiMAX [6, 7, 8, 9].

Relaying is also a major paradigm in Mobile Ad Hoc Networks (MANETs). Based on a CSMA-CA MAC, mobile devices must share the wireless medium. Considering the ad hoc and large scale nature of MANETs communication, efficient relaying becomes critical. Conceptually, efficient multi-hop communication in MANETs may be achieved by optimizing either the temporal or spatial reuse of the wireless channel, in other words by controlling the number of mobile terminals sharing the channel at the same time.

On the temporal reuse aspect, the well known *broadcast storm* effect is a typical issue of uncontrolled multi-hop broadcasting in MANETs. Known as *Topology Management (TM)*, a large literature has been proposed to mitigate this aspect either by employing graph theory concepts such as *dominating sets*, possibly enhanced with geographical considerations, or by probabilistic approaches where relays are selected based on probabilistic distributions. A survey of the various techniques may be found in [10, 11].

On the spatial reuse, one approach, known as *Topology Control (TC)* [12, 13], aims at adjusting the transmit power in order to only reach optimally selected relays. Unlike TM, each reachable node is a relay in TC. Unfortunately, guaranteeing an optimal spatial reuse requires an initial topology vision as large as possible, which is provided in practice by beacon messages being sent at the maximum allowed transmit power. Once this initial information is obtained, the transmit power may be adjusted, but the process must be executed again upon topology changes. For dynamic network topologies as found in VANETs, the spatial reuse benefit from a reduced transmit power might not be reached if TC solutions require frequent transmissions at the maximum allowed transmit power.

From a capacity perspective, Tavli illustrated in [1] that single-hop broadcast or multi-hop broadcast asymptotically scale as $\Theta(1)$. The conclusion from his study is that multi-hop broadcast is not more efficient than single-hop broadcast. Tavli's study however differs from ours, as he assumes that each node relays each received packet independently to its own transmissions, whereas we study the impact of packet multiplexing by multi-hop relays.

In [14], the authors investigated the proper progress, called "hop-distance", to be used in a multi-hop relaying configuration. Only considering unicast flows, Gao *et al.* notably illustrated that the throughput could be improved by increasing the transmit power and thus the hop distance up to a limit after which the throughput drops. The authors explained this optimal hop-distance threshold by the negative impact generated by too many interfering unicast flows. Investigating and finding this optimal threshold is part of the objective of our paper. Yet, the conditions in our study are particularly more challenging than those assumed by Gao *et al.*. Indeed, assuming a network of n vehicles, each of them having m neighbors, the process of beaconing is going to generate up to $n \cdot m$ flows in total.

Considering the delay requirements from VANET applications for traffic safety, relaying is usually not favored if the intended vehicles can be reached using a higher transmit power. Yet, it has been shown in [15, 16] that single-hop beaconing occupies a significant part of the channel capacity and may also lead to wireless channel congestions. Consequently, multi-hop beaconing based on efficient relaying mechanisms might still be required to increase the spatial reuse and to reduce the channel congestion.

Efficient relaying mechanisms could be inspired from related work on multi-hop broadcasting in VANETs and, more generally, in MANETs. Here, two major directions are typically found: probabilistic and deterministic broadcasting [10], possibly enhanced by geographical information. As we do not focus on efficient relaying itself in this paper, we only provide selected related work to illustrate the mechanisms. On the probabilistic side, Bai *et al.* proposed in [17] an adaptive solution for different traffic situations which alternates between *gossiping*, or the process of relaying with a probability p, and *store-carry-forward*.Bako *et al.* integrate position information to weight the gossiping probability p. Deterministic approaches instead let nodes, which are located in a given area, contend for a forward by introducing a retransmission timer which usually is based on the geographical progress. This mechanism may typically be found in [18], [19] or in [20]. The MHVB protocol [21] is also worth mentioning as it is specialized on the multi-hop dissemination of beacons in VANETs. Also based on a contention mechanism, MHVB further integrates message multiplexing strategies to reduce the overhead in the forwarding of received messages.

The process of beaconing is a particularly challenging broadcast configuration. On the one hand, single-hop broadcast may generate an unacceptable load on the wireless channel, while on the other hand, multi-hop beaconing requires complex relaying mechanisms. The question however is whether multi-hop beaconing with piggybacking is effectively able to reduce the load on the channel compared to single-hop and if so, what are the influencing factors.

3. COMPARISON

As motivated in the introduction, we address a simple pratical and fundamental question: can the congestion, which is generated on the channel solely by periodic beacons, be reduced if beacons are transmitted with a low transmit power, relayed over multiple hops and piggybacked into a node's own beacon transmission instead of being transmitted with high power over one hop only? By relaying beacons over multiple hops the same dissemination distance as in the 1-hop case can be reached, however with the benefit of an increased spatial reuse of the wireless channel. Since an uncontrolled relaying of broadcasts has shown to scale very badly, due to the well known broadcast storm problem, we make use of the ideas behind the efficient multi-hop broadcast protocol called MHVB [21] in which only 'optimally' located relays shall forward beacon messages and piggyback them with their own beacon transmission.

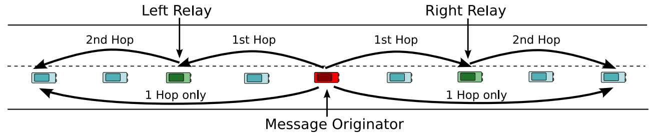

Figure 1: Illustration of the different dissemination concepts for beacons in a simple highway scenario: beacons are either disseminated over multiple hops (e.g. over 2 hops) or over 1 hop only.

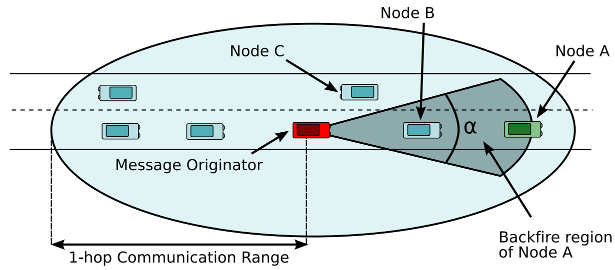

Figure 2: Illustration of the backfire concept: when a node receives a beacon message from a sender and retransmits the message, it will cancel a possibly running contention timer of vehicles located inside its backfire region. In this example, node A is retransmitting the message from the originator and would therefore cancel the contention timer of node B (but e.g. not of node C).

In the following subsections we first describe the core elements of the MHVB protocol on which we base our study. Afterwards, we explain the methodology by which we address the raised question and in particular motivate the need for an analytical model for the ideal case where no packet collisions occur and where radio propagation is deterministic. We then describe how we increase the realisms step by step through simulations, e.g. by considering aspects of packet collision and channel fading. We finally complete our comparison description by introducing several performance metrics and mentioning additional aspects which have to be considered in order to perform a fair comparison.

3.1 Dissemination of Beacons

This study compares the performance of two fundamentally different approaches which can be applied in order to broadcast periodic status messages up to a desired dissemination range: in the first and simple approach, beacons are broadcast with a transmission power which is sufficiently high to reach vehicles up to the dissemination range directly; in the second approach beacons are transmitted with a low transmit power, relayed and piggybacked by neighboring nodes until the desired dissemination range is covered.

Figure 1 illustrates the two concepts for a basic highway scenario where only two dissemination directions are considered. Assuming that the wireless channel is not fading, i.e., radio propagation is deterministic and successful beacon reception depends only on the distance between originator and receiver, and that MAC is able to synchronize the packets such that no collisions are observed, both approaches will deliver the beacon message to all intended receivers.

Disseminating beacons in a single-hop dissemination scenario is straightforward, since in the most simple case all vehicles use the same fixed transmit power, beaconing frequency and message size. In comparison, an efficient multi-hop dissemination approach is much more complex. Hence, the MHVB protocol consists of 4 complementary mechanisms, which enable a fast and efficient forwarding of beacon messages over multiple hops: (i) a *contention-based timer* which, with respect to the delay between message reception and the actual forward, favors the forwarding of messages by nodes with an increasing distance between sender and receiver; (ii) a so called *backfire algorithm* which suppresses redundant retransmissions; (iii) a *multiplexing of messages* to reduce the overhead created by packet headers and (iv) a *dynamic scheduling* of beacon transmission times to increase the efficiency of the backfire algorithm.

The contention-based timer is a concept that has already been used in previous studies for the dissemination of messages in highly mobile networks [22, 20]. Basically, it is a mechanism to determine how long a node should wait before relaying a received message. Depending on the distance to the sender of the message, the time to wait before forwarding the message can be either zero or anything up to a maximum contention or waiting time: in general, a receiver which is very close to the sender will contend or wait longer than a receiver which is located further away.

When using only the contention-timer and no additional mechanism, all nodes will still forward, which is not better than flooding. To solve this issue, the MHVB protocol introduces a *backfire algorithm* which cancels the contention-timer of a node receiving a retransmission of the same message from a different node located further away. As illustrated in Figure 2, the contention-timer of node B is canceled if the retransmission was already performed by node A, located further ahead, and if node B is located within the so called backfire region of node A. As shown, the backfire region is spanned and restricted by an angle α, thus α limits the area in which retransmissions are suppressed. In our illustration, node C will not be backfired, since it is located outside of A's backfire region. Due to this 'sectorial' backfire the dissemination of beacon messages into all directions is guaranteed.

The third mechanism addresses the multi-hop overhead issue: every time a node forwards a beacon message, it will not only retransmit the content of the message, but also add header information such as physical layer and medium access layer control data or security related information. By not forwarding a message immediately after the expiration of the contention-timer and instead delay the forwarding until an own periodic beacon message has to be transmitted, it is possible to multiplex the (to be forwarded) message and the own message into one single packet and save the overhead of one header. The extent of what can be the benefit is even increased if several contention-timers expire prior to the next beacon transmission and several messages are multiplexed.

Obviously, the overhead which can be saved by multiplexing heavily depends on the size of what is considered as a header. In VANETs for instance, where periodic beacon messages will probably be secured by signatures, one could consider the signature as header information as well. By not signing every single beacon message but only the whole packet, the overhead could be reduced dramatically, however, with the loss of having and end-to-end security for beacon messages.

Unfortunately, multiplexing introduces a major disadvantage: it breaks the backfire algorithm. Since with multiplexing optimally located relays might delay the forwarding up to the next own beacon transmission, it is possible that nodes located less optimally, i.e., nodes which should wait longer than the optimally located node, will forward earlier. The efficiency of the contention-timer and the backfire algorithm is simply killed in such a situation. In order to increase the efficiency again, i.e., optimally located nodes forward earlier than less optimally located nodes, the forth mechanism, called *dynamic scheduling*, re-schedules the transmission time of the next own beacon message such that the (to be forwarded) message can be multiplexed and relayed earlier. Since this dynamic scheduling leads to an increased beaconing frequency (every time a node re-schedules its next own transmission to an earlier point in time, the interval between two successive beacons is decreased) and thus to more beacons which have to be disseminated, we apply dynamic scheduling only to the n optimally located receivers. To control the number of vehicles n that are allowed to perform dynamic scheduling, a parameter called *dynamic scheduling threshold* is introduced. This threshold defines the minimum required distance between sender and receiver beyond which a receiver will re-schedule its next beacon transmission in order to forward the received message earlier than less optimally located nodes.

In combination, the described mechanisms facilitate an efficient broadcasting scheme to disseminate periodic beacon messages over one or multiple hops. The dissemination stops, whenever a desired maximum dissemination range has been reached or whenever the age of the to be forwarded information exceeds a maximum time to live (TTL) threshold.

3.2 Methodology

Comparing fundamentally different communication concepts requires a careful methodology as the validity of the results heavily depends on how the comparison is performed or which system dynamics and effects are considered. In order to observe a progressive impact of different effects, we follow a stepwise approach. Throughout our comparison, we look at a simplified scenario in which vehicles are placed on a straight line with either a fixed inter-vehicle spacing or by using an average vehicle-density. We will look at different vehicle-densities and consider two dissemination directions in our scenario.

In our first step, we start with an analytical consideration of the problem and develop a model to compute the channel congestion, i.e. the channel load, when dissemination beacons up to a certain distance over one or several hops. In the analysis we assume an optimal dissemination protocol and ignore the impact of packet collissions and channel fading: every vehicle transmits beacon messages at a fixed frequency, e.g. 5 Hz, and only acts as a forwarder for neighbors for which it is the optimal relay. A beacon will successfully be received by a neighbor, if the distance between the sender and the receiver is smaller or equal than the deterministic

1-hop communication range[2].

Afterwards, we study the problem through simulations in order to increase the degree of realism and to compare the concepts not only with respect to the load on the channel but also with respect to dissemination reliability and latency. Our second step therefore adds the possibility of packet collissions and evaluates the impact on dissemination efficiency and reliability. In our last step, we introduce channel fading characteristics by applying probabilistic radio propagation models, i.e., the Nakagami-m distribution, and study whether fading will degrade or increase the performance of the dissemination process.

3.3 Evaluation Metrics

Performing a fair comparison between two fundamentally different concepts requires carefully selected evaluation metrics. For instance, although we primarily focus on the impact of single- and multi-hop beaconing on the channel load, we also have to consider aspects such as dissemination delay or probability of successful beacon reception.

We begin with the primary metric which we will use to compare the channel congestion of both approaches, the channel load metric.

DEFINITION 1 (CHANNEL LOAD).
The channel load is the amount of data traffic in bits/sec a node u is exposed to during a time period t. More specifically, the channel load is the sum of all transmissions during t which would prevent node u from transmitting its own packet, independent of whether node u can actually decode each transmission or not.

The above definition is closely related to the CSMA concept used in 802.11 and basically a metric which describes how many transmissions (or more generally, bits) have to be coordinated by the medium access layer during a time period t. Compared to the channel busy time, which could be measured by a real wireless chipset, the channel load can not be measured. It is rather an abstract concept and able to quantify the real congestion of the channel including overlapping transmissions. In other words, the channel load is the sum of all transmissions which (on their own and without the help of other interfering transmissions) would block a node from sending[3]. With respect to our comparison scenario, the periodic exchange of status messages, we will use this metric to (i) calculate the expected channel congestion in the optimal case without running simulations and to (ii) evaluate the channel congestion as experienced by vehicles when actually running simulations. For the calculation in the analytical part, we use a deterministic radio channel model, and assume that a transmission blocks every neighbor within the carrier sensing range. The channel load as experienced by a node u is then simply the sum of all transmissions for which node u is withing the carrier sensing range. In our simulations, we take a god's perspective and monitor all transmissions which arrive with a signal strength higher than the carrier sense threshold. Please note that the monitored channel load in our simulations is derived after a simulation has been finished and that the computation does not influence the dissemination protocol in any way. By a calculation of the channel load in the optimal case, where the dissemination is successful and as efficient as possible, we are not only able to determine a lower bound for the channel congestion but are also able to check how close this lower bound is met in a simulated and non-optimal system.

Apart from the channel utilization, we also look at the provided neighborhood awareness and the latency of received information. More precisely, we look at the probability of receiving at least one of the past X beacons sent by neighbors and at the average age of the received beacon information. Considering not only the basic probability of single- and multi-hop message reception and instead investigating the probability of receiving at least 1 out of the last X transmitted messages by each neighbor, we are able to get a good impression of the average awareness and are able to perform a fair reliability comparison between single- and multi-hop beaconing.

DEFINITION 2 (NEIGHBORHOOD AWARENESS).
The neighborhood awareness is a metric which describes the probability that a node v is aware of its neighboring nodes and is calculated with respect to the distance between node v and its neighbors. More specifically, the neighborhood awareness is expressed as the probability of having received at least one beacon message within the past second.

DEFINITION 3 (BEACON INFORMATION AGE).
The beacon information age is the average age of received status informations and is calculated with respect to the distance between the originator and the receiver. It can also be interpreted as the average inter-reception time between two beacons of the same originator.

As mentioned above, protocol theory and protocol behavior in a dynamic system might be different, not only with respect to the experienced channel load. Even the intended or desired dissemination range might not be possible to achieve due to packet collisions or radio propagation issues. And though it is obvious that multi-hop dissemination implies a higher latency for beacons which are received over more than one hop (due to contention and channel access delays), we evaluate the resulting average age of received status informations to determine the extent of the increased latency.

During the simulative evaluation of the MHVB protocol in Section 5, we will further look at the *beacon sent ratio* and the *number of retransmissions* as metrics to determine whether the protocol behaves as intended. The beacon sent ratio is basically the number of beacon messages that a vehicle transmits per second and is used to determine whether vehicles stick to the configured beaconing frequency or not, e.g. due to the dynamic scheduling of the MHVB protocol. The number of retransmissions are an indicator for the efficiency of the protocol in terms of how many relays are used to deliver a beacon up to the dissemination range.

4. ANALYSIS

In this section, we develop an analytical model to compute the channel load as a function of the intended dissemination

[2]The deterministic 1-hop communication range is the distance up to which, given a fixed transmit power, the well known Two-Ray Ground propagation model provides a sufficiently large signal strength in order to successfully decode a transmission

[3]According to the 802.11 standard specification, a node is blocked to send an own transmission whenever the physical layer senses a signal with a sufficiently large strength or when it is currently in reception or transmission mode.

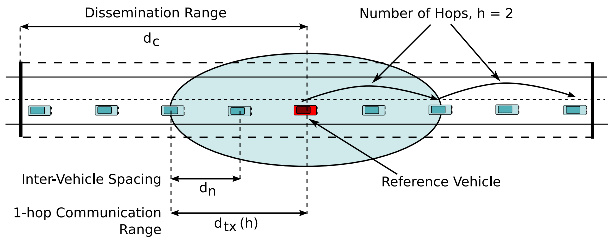

Figure 3: Illustration of the considered scenario for an analytical estimation of the channel load depending on the intended dissemination range for beacon messages, the number of hops to cover this range and the inter-vehicle spacing distance.

Symbol	Meaning
d_c	Intended coverage range
h	Number of hops to be used
d_n	Inter-vehicle spacing
s_m	Size of a beacon payload
s_h	Size of a beacon header
Function	**Meaning**
$l(h)$	Overall channel load experienced by each node
$d_{tx}(h)$	1-hop communication range
$n_{d,tx}(h)$	Number of messages originated locally
$n_{d,rx}(h)$	Number of directly received messages
$n_{i,tx}(h)$	Number of forwarded messages
$n_{i,rx}(h)$	Number of indirectly received messages

Table 1: Overview of the symbols and functions used in the analytical model.

range, the number of hops to be used to cover this range, the vehicle density and the size of the message header and payload. The model considers, as described in Section 3.2 and illustrated in Figure 3, a very basic scenario in which vehicles are placed with a constant inter-vehicle spacing along a straight line.

In order to calculate the load in the network, we are going to sum up all transmissions which a node is exposed to during one second. According to Definition 1, this includes all transmissions with a signal strength higher than the minimum receiver sensitivity, i.e., all transmissions from within the 1-hop communication range, or with a signal strength higher than the carrier sense threshold. To increase comprehensibility we set the carrier sense threshold equal to the minimum receiver sensitivity, though the carrier sense threshold is an artifical parameter which of course could also be lower than the minimum receiver sensitivity.

Without loss of generality, we consider only one periodic beacon transmission of each node per second and calculate the number of messages a node will receive by 1-hop directly, the number of messages a node will receive indirectly by more than 1-hop and the number of messages a node will forward. The channel congestion each node will experience is then given by the number of directly received and transmitted messages multiplied with the sum of header and payload size plus the number of indirectly received and forwarded messages multiplied with the header size.

In our model, we denote the intended dissemination range up to which beacon messages shall be broadcasted by d_c, the number of hops to cover this range by h, the distance between vehicles by d_n, the size of a beacon header by s_h and the size of the beacon payload by s_m. An overview of the abbreviations we use and the preliminary functions which constitute the model is given in Table 1. In the following we will derive all preliminiary functions and combine them in order to obtain the final function $l(h)$.

First, we derive the 1-hop communication range $d_{tx}(h)$ as

$$d_{tx}(h) = d_c/h \tag{1}$$

which is the minimum 1-hop communication range required to reach all vehicles within the dissemination range by h hops or less. Please note that this range is only sufficient if relaying nodes are located exactly at the border of the deterministic 1-hop communication range. Since we want to estimate the lower bound of the channel load, we assume that this will be the case and that forwarding will only be performed by such nodes.

The number of beacon messages per second each node sends itself, i.e., which are originated locally, is alway one, independent of the number of hops. So

$$n_{d,tx}(h) = 1 \tag{2}$$

The number of beacons each vehicle receives directly from its neighbors depends on the communication range and the vehicle density (or inter-vehicle spacing) and considers receptions from both directions. So

$$n_{d,rx}(h) = 2 \cdot \frac{d_{tx}(h)}{d_n} \tag{3}$$

Since the vehicles are placed on the road with a uniform inter-vehicle spacing and since the communication range is fixed and deterministic, each vehicle acts as the designated forwarder for exactly one vehicle located to its left and one vehicle located to its right. These two vehicles are labeled *forwarding sources* in the following and are not necessarily the closest neighbors – this is only the case if the communication range $d_{tx}(h)$ is equal to the inter-vehicle spacing d_n. In addition, each vehicle will act as an indirect forwarder for messages which have been relayed by these *forwarding sources*. Hence, the total number of forwarded messages depends only on the number of hops h and is expressed by

$$n_{i,tx}(h) = 2 \cdot (h-1) \tag{4}$$

For instance, if the number of hops h is set to 2, each vehicle will forward only one beacon per direction — one beacon which has been sent by a node to its left and one beacon which has been sent by a node to its right.

Further, the number of messages a vehicles receives indirectly, i.e., the number of messages for which the vehicle is not the designated forwarder, is the product of the number of vehicles from which it receives beacons directly and the number of messages each node forwards. Thus,

$$n_{i,rx}(h) = n_{d,rx}(h) \cdot n_{i,tx}(h). \tag{5}$$

Now that we have all preliminary functions, we can combine them to obtain the overall load each node will experience. Therefore, we have to multiply all direct transmissions and receptions with the sum of header and payload size and add the result to the product of all indirect transmissions and receptions with the payload size.

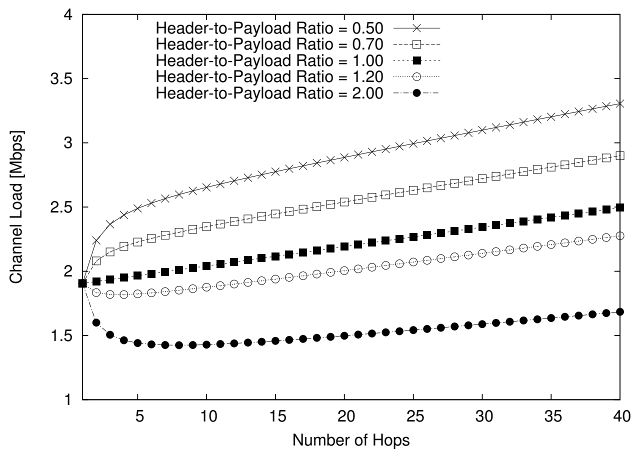

Figure 4: Lower bound of the channel load w.r.t. the number of hops for different header to payload ratios. The underlying scenario has a vehicle density of 60 vehicles/km, the cumulative size of the header plus payload is always 378 Bytes, the intended coverage range is 1000 m and a beacon frequency of 5 Hz is assumed.

$$l(h) = (n_{d,tx}(h) + n_{d,rx}(h)) \cdot (s_h + s_m) + (n_{i,tx}(h) + n_{i,rx}(h)) \cdot s_m \quad (6)$$

In Figure 4, we have plotted the overall channel load for a fixed vehicle density but different header and payload sizes. As illustrated the load increases monotonically with the number of hops if the ratio between header and payload size is less or equal than one. When the ratio is greater than one, i.e., the header of a message is greater than the payload itself, the channel load initially decreases with an increasing number of hops, finds a minimum and then increases again. In that configuration, the minimum could be considered as the optimal number of hops for multi-hop beaconing.

5. SIMULATION

In this section we study the impact of packet collisions and channel fading on the efficiency and reliability of single-hop and multi-hop based beacon dissemination. Therefore we use the network simulator ns-2.33 [23] which provides an overhauled MAC/PHY-model adapted to the specifics of the envisioned standard for inter-vehicle communications, IEEE 802.11p, and which we have configured to the values listed in Table 2.

In Section 5.1 we will first describe the simulation setup and the configuration of the single-hop and multi-hop scenarios. Section 5.2 and Section 5.3 then present and discuss the obtained results with respect to the metrics defined in Section 3.3 and under the influence of packet collissions and channel fading respectively.

5.1 Simulation Scenario

In our simulations, vehicles are placed on a straight, 7 km long road with an average inter-vehicle spacing of either 50 m or 16,55 m — which corresponds to 20 vehicles/km and 60 vehicles/km respectively. Two different inter-vehicle spacings are used in order to study the impact of the vehicle density. In addition, we do not consider any movement of vehicles in order not to add any additional effects which have not been considered in the analysis. We finally apply a jitter to the locations of the vehicles, as otherwise the distances between a sender and receiver pair would always be a multiple of the inter-vehicle spacing.

Parameter	Value
Radio propagation model	Two-Ray Ground, Nakagami-m, $m = 1, 3$
IEEE 802.11p data rate	6 Mbps
Channel bandwidth	10 MHz
Preamble length	40 μs
PLCP header length	8 μs
Symbol duration	8 μs
Antenna gain	0 dB
Antenna height	1.5 m
Noise floor	-99 dBm
Receiver sensitivity	-91 dBm
Carrier sense threshold	-91 dBm
SINR for preamble capture	5 dB
SINR for frame body capture	10 dB
Minimum contention window	15
Slot time	13 μs
SIFS time	32 μs

Table 2: Configuration of the 802.11p MAC and PHY in ns-2.33

For both vehicle densities we created five scenario instances, which differ only with respect to the specific locations of the vehicles. All vehicles are configured to transmit 5 beacon messages per second with a datarate of 6 Mbps. The intended dissemination range is set to 1000 m and the number of hops to cover this range to 1, 2 or 4 hops. Consequently, the transmission power is set to 21.96 dBm, 10.85 dBm or 4.83 dBm, which corresponds to 1-hop communication ranges of 1000 m, 500 m and 250 m under Two-Ray Ground.

Parameter	Value
Beacon generation rate	5 Hz
Intended dissemination range	1000 m
Backfire angle	30 °
Max contention time	100 ms
Maximum number of hops	1, 2, 4
Transmission power	1-Hop: 21.96 dBm, 1000m 2-Hop: 10.85 dBm, 500m 4-Hop: 4.83 dBm, 250m
TTL	1.0 secs
Header size	28 Bytes / 206 Bytes
Payload size	350 Bytes / 172 Bytes

Table 3: Configuration of the nodes for the dissemination of periodic status messages up to a distance of 1000 m.

The maximum TTL, which is used during the dissemination to decide whether a message should still be forwarded, is set to 1.0 sec. The dynamic scheduling threshold is set to a distance such that in each scenario only $n = 1$ node will be able to perform dynamic scheduling. Regarding the header and payload size, we assume a MAC/PHY header of 28 Bytes, a security trailer of 178 Bytes and a beacon payload of 172 Bytes. Depending on whether the security trailer is considered as part of the header or not, the overhead, which can be saved due to message multiplexing, is either 28 Bytes or 206 Bytes. As a result, the payload size is either 350 Bytes (including security trailer) or 172 Bytes (without security trailer). Due to space restrictions and the fact that

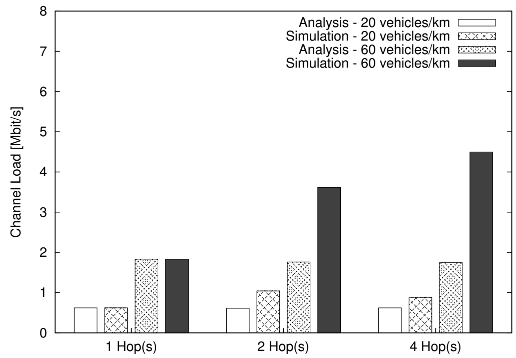

Figure 5: Comparison of the analytically obtained lower bound of the channel load and the observed values in the simulations for different vehicle densities and a header to payload ratio greater than one.

we would like to illustrate a typical configuration which can theoretically benefit from multi-hop beaconing (according to our analysis this is the case when header to payload ratio is greater than one), we only show the results for which the security trailer is considered as part of the header.

In the simulation, we will first use the Two-Ray Ground propagation model to study solely the effect of packet collisions on the performance of the dissemination. Afterwards, we will introduce channel fading characteristics in terms of a Nakagami-m distribution for the calculation of average received signal strengths of packets and evaluate whether fading helps to increase the dissemination performance or not. Since ns-2 is a packet-level simulator, fading is only applied to consecutive packets and not to single packets, i.e. we assume that either the channel is not fading during the reception of a single packet or that wireless chipsets are able to mitigate channel fading by the use of advanced techniques such as time-domain channel estimation [24] or differential modulation [25].

5.2 Impact of Packet Collisions

First, we study the channel loads which are observed in the simulations and compare them with the values we obtain through the analytical model. Since the model provides a lower bound, the observed channel loads should be equal or greater. Figure 5 shows the observed and the analytical results side by side for the 1, 2 and 4 hop(s) configuration and both vehicle densities. As it can be seen, the 1-hop configuration matches the analytical lower bound perfectly. This is no surprise, since all vehicles transmit their beacons periodically at 5 Hz. With the 2 and 4 hop configuration, the observed channel loads are higher than what we computed analytically for an optimal dissemination, whereas the difference between analysis and simulations is small when looking at the 20 vehicles/km scenario and quite significant in the 60 vehicles/km scenario.

The explanation for either a big or small difference is given by Table 4 and Table 5, which list the observed *beacon sent ratios*[4] and the *average number of retransmissions*[4] per beacon message for each configuration and scenario. For instance, we can observe increased beacon sent ratios in the 20 vehicles/km scenario, namely 5.70 Hz and 5.22 Hz, and

[4]See definition on page 5.

	1 Hop	2 Hops	4 Hops
20 vehicles/km	5.00 Hz	5.70 Hz	5.23 Hz
60 vehicles/km	5.00 Hz	5.01 Hz	5.01 Hz

Table 4: Observed beacon sent ratios for single-hop and multi-hop beaconing, a payload size of 172 Bytes and different vehicle densities.

more or less no increase in the 60 vehicles/km scenario. An increased beacon sent ratio indicates that nodes apply dynamic scheduling and that optimally located nodes are forwarding earlier than less optimally located nodes. According to Table 4, dynamic scheduling is therefore nearly not performed at all in the 60 vehicles/km scenario. The reason is quite simple: due to the higher number of vehicles in the 60 vehicles/km scenario, the congestion on the channel as well as the packet collission probability is higher and thus the probability that an optimally located node receives and forwards the message successfully is much lower than in the 20 vehicles/km scenario. Consequently, a re-scheduling of the next transmission time is a very rare event. This observation has a direct impact on the average number of retransmissions per beacon message, as illustrated in Table 5. While an optimal dissemination would require only 2 or respectively 6 retransmissions in the 2 and 4 hop configuration, we can observe 4.32 or 9.57 retransmissions in the 20 vehicles/km scenario and 6.44 or even 19.38 retransmissions in the 60 vehicles/km scenario. Obviously, the applied dynamic scheduling activity in the 20 vehicles/km scenario backfires running contention timers of less optimally located nodes and therefore able to prevent redundant retransmissions. On the contrary, the missing dynamic scheduling in the 60 vehicles/km scenario leads to a signifcant amount of redundant retransmissions.

	1 Hop	2 Hops	4 Hops
20 vehicles/km	0.00	4.32	9.57
60 vehicles/km	0.00	6.44	19.38

Table 5: Average number of retransmission per beacon message for single-hop and multi-hop beaconing, a payload size of 172 Bytes and different vehicle densities.

However, reducing the dynamic scheduling threshold (see Section 3.1, page 4) in order to allow more vehicles to perform dynamic scheduling and thus increase the efficiency of the backfire algorithm does not always solve the problem of too many redundant retransmissions. Indeed, allowing more nodes to reschedule the next beacon transmission also leads to an increased beacon sent ratio, which in turn requires more retransmissions and which can lead to more retransmissions. In the 20 vehicles/km scenario the increased beacon sent ratio was not as significant, but with a higher vehicle density, a small increase can lead to counter-intuitive results. The selection of the optimal dynamic scheduling threshold is therefore a very difficult task and also different for varying traffic densities. As we could see above, a threshold that works good for 20 vehicles/km must not necessarily work good in a 60 vehicles/km scenario.

Figure 6 and Figure 7 show the provided neighborhood awareness and the age of the received beacon information

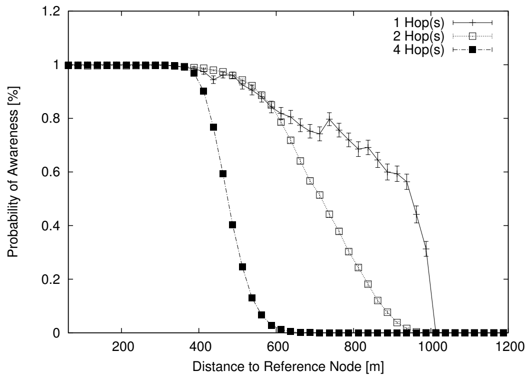

Figure 6: Probability of awareness (with respect to the distance) about surrounding nodes. Only the 2-hop configuration achieves a slightly better awareness as the 1-hop configuration.

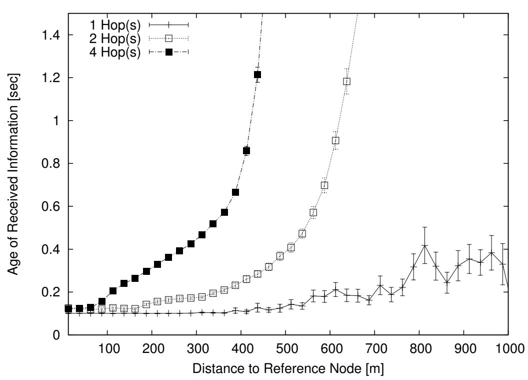

Figure 7: Average age of received neighbor information (with respect to the distance). Disseminating periodic beacon messages by 1-hop is always faster as over multiple hops.

with respect to the distance to neighbors for the 60 vehicles/km scenario. Although multi-hop provides an increased reliability for the successful delivery of individual messages (due to retransmissions), the resulting neighborhood awareness is not better than the awareness provided by the single-hop configuration. Remember, that the condition for awareness has been defined as the probability of having received at least one message within the past second (see Section 3.3, page 5). With respect to latency, it is clear that a multi-hop dissemination strategy will always be slower than a 1-hop approach, at least beyond the first hop. Figure 7 shows the extent of the increased delay: while the 1-hop configuration provides a constant delay of 100 ms up to a distance of 400 m (which is half the inter-arrival time) and a delay below 200 ms up to a distance of 700 m, the delay in the 2-hop and 4-hop configuration is increasing rapidly even for close distances and already above 1000 ms for distances beyond 60 m or 450 m.

5.3 Impact of Channel Fading

In this section, we will evaluate the impact of a fast-fading channel on the performance of the beacon dissemination. Therefore, we use the same scenarios as before and apply the Nakagami-m distribution on top of Two-Ray Ground

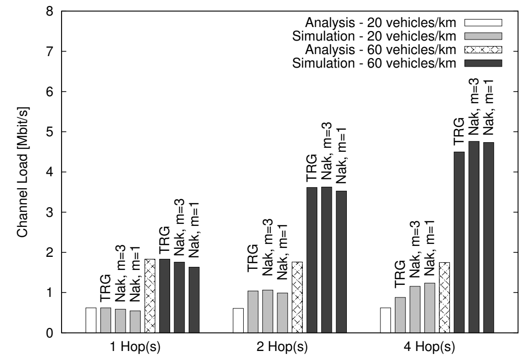

Figure 8: Comparison of the analytically obtained lower bound of the channel load and the observed values in the simulations for different vehicle densities, a header to payload ratio greater than one and with or without channel fading.

in order to mimic the behavior of a fading channel[5]. We set the m-parameter to 1 or 3 in order to study the effect of different fading intensities. For instance, with $m = 1$ we model a Rayleigh channel with severe fading conditions and with $m = 3$ we model a channel with medium fading conditions.

		20 vehicles/km		60 vehicles/km	
		f	ρ	f	ρ
2 Hops	TRG	5.70 Hz	4.32	5.01 Hz	6.44
	Nak, $m = 3$	6.25 Hz	4.39	5.18 Hz	6.80
	Nak, $m = 1$	6.23 Hz	4.70	5.23 Hz	7.50
4 Hops	TRG	5.23 Hz	9.57	5.01 Hz	19.38
	Nak, $m = 3$	7.67 Hz	10.34	5.06 Hz	21.16
	Nak, $m = 1$	6.91 Hz	10.88	5.21 Hz	22.27

Table 6: Observed beacon sent ratios f in Hz and average number of retransmissions ρ in a 5 Hz configuration for multi-hop beaconing, a payload size of 172 Bytes, different vehicle densities and different fading intensities.

Figure 8 shows the observed channel loads for various radio propagation conditions in comparison with the values computed by the analytical model. As illustrated, it is not possibel to conclude that an increased channel fading leads to a higher or lower channel load. As already stated in the previous section, the multihop dissemination is very sensitive to changing conditions and a configuration that showed to be successfull before, can behave different after the change.

By looking at Table 6, which shows the observed beacon sent ratios and the average number of retransmissions per beacon, we can say that an increased channel fading leads to an increased beacon sent ratio and an increased number of redundant retransmissions. Due to the increased number of beacon transmissions and retransmissions the chance to successfully receive at least one message within one second is increased. Combined with the fact that fading allows to

[5]In a fading channel the probability to successfully receive a packet within the deterministic communication range is reduced, but at the same time, the possibility to receive a packet beyond the deterministic communication range is introduced.

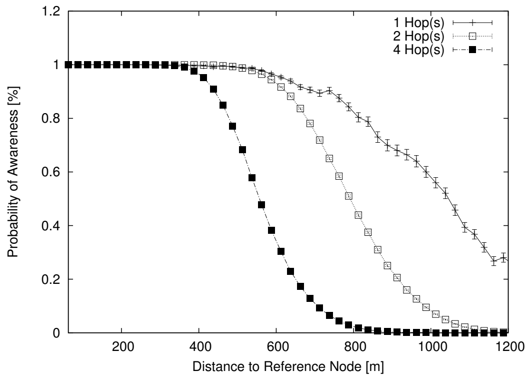

Figure 9: Probability of awareness (with respect to the distance) about surrounding nodes when a Rayleigh fading channel is modeled.

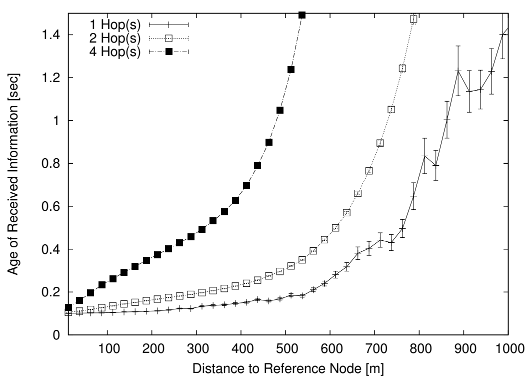

Figure 10: Average age of recveived neighbor information (with respect to the distance) when a Rayleigh fading channel is modeled.

receive a message even beyond the (previously used) deterministic communication range, the provided neighborhood awareness is increased as well, see Figure 9.

Since fading reduces the probability of reception for individual packets, the average inter-arrival time, i.e. the age of the received information, should be increased in a fading channel. By looking at Figure 10, where the age of the received information is plotted for a Rayleigh channel, wee see that exactly this is happening. For all hop configurations we observe an increase (compared to Two-Ray Ground, see Figure 7) of the average age, whereas the increase is more significant in the 1-hop configuration. Due to the higher reliability of multi-hop, the inter-arrival time is not increasing too much.

6. CONCLUSIONS

The periodic local broadcast of status information is a key communication pattern in VANETs and has been widely studied in the past. The particular problem of how to reduce the congestion of the wireless channel, specifically the congestion which is solely caused by periodic beacons, has gained a lot of attention and fundamentally different solutions – single hop transmission at high transmit power or multi-hop transmission and relaying at lower transmit power – have been proposed. However, a fair and thorough comparison considering the impact of intelligent relaying was yet missing.

In this paper, we presented a framework for a fair comparison of these conceptually different solutions and used it to know whether an efficient multi-hop beaconing can reduce the load on the channel due to an increased spatial reuse and intelligent forwarding techniques such as message multiplexing. For that matter, we developed an analytical model providing a lower bound of the channel load for single-hop and multi-hop beaconing. We showed that in the one-dimensional and optimal scenario the load can be reduced, thanks to beacon multiplexing, if the header to payload ratio is greater than one. Unfortunately, simulations showed that the theoretical reduction of the channel load cannot be exploited if packet collisions, 'non-perfect' channel conditions and suboptimal relaying are considered.

We would like to note that multi-hop beaconing could definitively be required in situations where non-line-of-sight areas forbid a full coverage by single hop beaconing. In future work, we will investigate whether optimizing a multi-hop relaying protocol could help getting closer to our analytical lower bound. Second, we will extend the analysis and comparison to consider also urban scenarios, in which multi-hop beaconing might be necessary in order to bypass radio obstacles such as buildings or trucks and to enable information dissemination in non-line-of-sight areas as well.

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