A Multi-Layer Approach for Improving the Scalability of Vehicular Ad-Hoc Networks

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Abstract. Inter-Vehicle Communication (IVC) and its diverse possibilities for telematics and on-line safety applications have led to great interest in both academia and industry. Especially the broadcast-based dissemination of automatically generated, local danger warning messages in such networks bears huge potential to increase both driver safety and comfort. However, the shared wireless medium that is used for the data exchange may quickly become overloaded. To enable inter-vehicular networks that work properly in case of varying network load and vehicle density, novel approaches must be defined that ensure the reliable and timely delivery of highly relevant messages. In this work, we propose a holistic framework that spans over both the application and the MAC layer and facilitates the scalability of VANETs by introducing information differentiation. We present diverse strategies to modify the packet broadcast sequence as well as the MAC functionality according to the benefit which messages are expected to provide to adjacent network nodes. A comprehensive simulation setup is leveraged to prove the advantages of our concept.

1 Introduction

Over the last years research in the area of mobile ad hoc networks (MANETs) has led to the emergence of many different possibilities for practical applications. One specific use case scenario of MANETs is vehicular ad hoc networks (VANETs) that are envisioned to spontaneously setup between cars and autonomously control message exchange.

Many applications can be thought of in the context of VANETs. Especially the improvement of safety for both passengers and vehicles in general is one major goal using wireless communication between vehicles. Inter-vehicular communication provides a new way of exchanging up-to-date information between vehicles very fast. VANETs can be realized using one of several existing wireless communication technologies. However, the conventional IEEE 802.11 WLAN technology and its sub-specifications have become the most common technology proposed. Besides advantages like maturity of the technology, robustness, usability, and many others this technology also has significant drawbacks, especially in the context of V2V networks. One major issue related to any wireless technology using a shared medium is the very limited channel and hence network capacity [5]. With increasing number of network nodes the capacity is proportional to $\mathcal{C} = \frac{1}{\sqrt{N}}$, where N represents the number of nodes. This limited capacity leads to scalability issues for future VANETs. Moreover, a V2V network with few nodes or low data traffic will work fine, but a network with many nodes and/or high data load will break down. This effect is also known under the term Broadcast Storm [11]. Due to the fact that the wireless medium is shared between nodes collisions occur, leading to a further decrease in network capacity. Therefore, new strategies for data dissemination in VANETs have to be designed, tackling this scalability and capacity issue.

In this paper we present a novel approach to tackle the scalability challenge of V2V networks. We use a combination of different methodologies on two layers of the OSI reference model and apply data traffic differentiation according to the benefit messages are expected to provide to neighbor nodes [3].

The remainder of the paper is structured as follows. In Sec. 2 we present the most important related work to the topic. In Sec. 3 we present our multi-layer approach and explain the concepts used in detail. In Sec. 4 we present the simulation setup used to evaluate our approach and give selected simulation results proving the capabilities of this concept. The paper closes with a conclusion and outlook in Sec. 5.

2 Related Work

The use of benefit (also often referred to as utility) for network optimization has already been introduced in [10]: The data rate with which nodes may transmit is adjusted according to the respective packets' utility.

Some publications already highlighted the necessity to treat data traffic in VANETs according to its respective relevance. For example in [15] the authors investigate the effects of a prioritized medium access scheme in the context of highly loaded VANETs. The authors introduce an implementation of the Enhanced Distributed Channel Access (EDCA) functionality which is the basis of the IEEE 802.11e standard [7]. A scenario comprising 600 vehicles driving around is simulated, where all of them continuously transmit data packets. 599 of those vehicles apply conventional parameters influencing the medium access functionality, whereas one vehicle makes use of another parameter set and thus may access the shared medium faster than its non-prioritized neighbor nodes. It has been shown that the reception probability of the data broadcasted by the prioritized vehicle could be significantly increased.

In [1] Chiasserini et al. compare various approaches to make broadcast communication more reliable and efficient. With the help of simulative studies, the implications of adapting the magnitude of the so called contention windows to the distance between sender and receiver of a certain message are evaluated. By introducing such a spatial traffic differentiation, the efficiency of broadcast-based message dissemination schemes can be improved. The greater the distance between the sending node and the recipient, the smaller the contention window is adjusted. Thereby, the likelihood that those nodes which reach a maximum number of new neighbors can be maximized, where retransmissions conducted by close-by nodes (which would only reach a small amount of new receivers) are reduced to a minimum.

In [4] Füßler et al. present a forwarding scheme where alterations of the contention window are used to prioritize messages. Increasing with the distance to the last message disseminator the contention window length decreases and channel access is more likely. With this scheme the likelihood that those nodes which reach a maximum number of new neighbors can be maximized. In addition, retransmissions conducted by nodes reaching only a small amount of new receivers are minimized.

In their paper from 2005 Torrent-Moreno et al. present a concept to fairly share the limited bandwidth in a fully deployed and locally overloaded VANET [16]. The presented approach uses a new power control mechanism. It aims at reducing the transmission range in a controlled fashion to reduce the interference range of the nodes, therefore reducing the network overload. However, the approach assumes a constant packet generation ratio and does not consider message content and its relevance for network nodes.

Previous results for our scheme have primarily been presented in [3,14,8].

3 A Holistic Multi-Layer Approach

To cope with the challenges presented above, we aim at a comprehensive approach [8] that spans over two layers of the OSI reference model: Mechanisms both in the application and the Medium Access Control (MAC) layer will allow for deploying scalable VANETs.

To describe the basic characteristics of our concept, the following idealized and simplified scenario can be studied. Suppose there are N (e.g., $N = 12$) wireless stations within mutual communication range. At one specific point of time (depicted in Fig. 1), each of them has at least one packet ready for broadcast. Since all network nodes have to share the wireless medium, only one of them is able to transmit at the same time. Each of the nodes $n_i(i \in [1, 12])$ has a dedicated interest in certain information (in the form of packets p) that can be quantified with the help of a so called benefit function $ur_i(p, t)$, which varies over time. To maximize the benefit provided to the whole network, a global scheduler, which has detailed knowledge on all the nodes' packets and their respective benefit functions, would conduct a two-step process. First, a node-internal packet benefit ranking is established: For each of the data packets $p_{ji}(j \in [1, P])$ that are enqueued at a specific node n_i, the benefit provided to all the adjacent nodes is thereby computed. The normalized network benefit (NNB) as shown in Equ. 1 is computed as the sum of the all the N nodes' individual benefit values provided by packet p_{ji} minus the benefit for the broadcasting node n_i. The packet providing the maximum benefit to all of the reachable neighbors is the packet the node should broadcast as the next one. However, the internal packet ranking is not sufficient to maximize the global, aggregate benefit, provided to the whole network. In fact, the twelve packets which have won the node-internal ranking process probably provide different benefit to the rest of the network.

$$NNB(i, j, t) = \frac{1}{N-1} \left[\left(\sum_{k=1}^{N} ur_k(p_{ji}, t) \right) - ur_i\left(p_{ji}, t\right) \right] \tag{1}$$

$$MaxNNB(i, j, t) = max_{i=1 \cdots N} \left\{ max_{j=1 \cdots P} \left[NNB(i, j, t) \right] \right\} \tag{2}$$

As a second step, an external ranking is to be established, which ensures that the node n_i, whose highest ranked packet provides the highest benefit to the network (maximum normalized network benefit, MaxNNB), finally is granted access to the shared, wireless medium. Equ. 2 represents both internal and external packet selection. For the application in a VANET environment, however, a global, central packet scheduler that is able to see the network from a bird's eye view is not feasible. Since VANETs are operated decentrally, packet scheduling must be realized without the help of any central entity. In fact, each node will have to approximate the benefit each of its packets provides to the adjacent nodes and thus establish a node-internal packet broadcast sequence. However, the limited knowledge of the nodes prevents the realization of a perfect schedule. None of the network nodes exactly knows about its neighbors' individual interest in information (which is represented by the respective ur-functions in Eqn. 1). Also, mechanisms will have to be found to realize an inter-node contention without any central entity polling the stations. Finally, real-world VANETs will not be limited to a small area as depicted above, where all nodes are within mutual communication range, moreover, they will probably span over large areas. Thus, the interference between different parts of the network will have to be considered to maximize the aggregate benefit throughout the whole network.

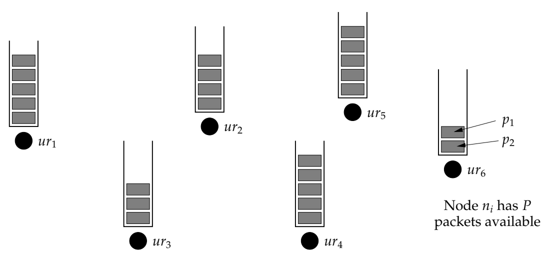


Fig. 1. Snapshot of an idealized example scenario

3.1 Application layer

The application layer comprises a data packet queue (for storing all packets that wait for medium access) and knows all application-relevant data of a network node such as geographical position, system time, a local memory containing all previously received information available, and thus is able to comprehensively evaluate the benefit a certain piece of information may provide to recipients in the neighborhood. Whenever a node is granted access to the medium, not the packet that has been waiting in the queue the longest time, but the one with the highest current benefit is selected for transmission.

For quantifying the expected benefit of traffic related messages ur, we take into account various parameters which can be associated with the *informational*-, the *environmental*- or the *message*-context. The informational context (parameters include e.g. distance to information source, time-of-day, information quality, information type, and rate of change) ensures that the specific data contained in the messages is adequately evaluated with regard to its benefit, where parameters from the environmental context (e.g. driving direction, vehicle speed, and roadtype) take into account the vehicular and network-specific situation, which may influence message benefit as well.

Finally, message-specific characteristics such as message age, last broadcast time, and last reception time play an important role for benefit determination. All of these parameters must be converted into preliminary benefit values with the help of so called sub-functions. A sub-function is devoted to quantifying the benefit a message would provide to neighbor nodes only with regard to one specific parameter. By summing up the weighted results of the sub-functions, a single benefit value per message can be computed. An exact benefit computation is presented in [14].

3.2 MAC layer

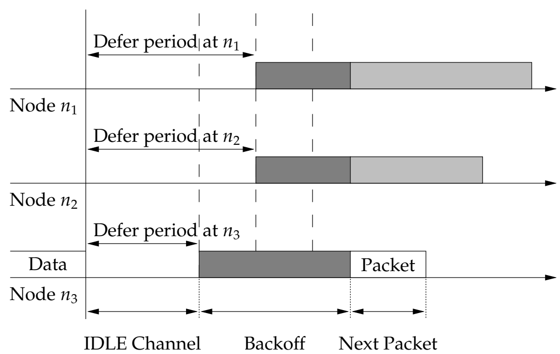


Fig. 2. Modifying defer-and backoff timers

After establishing a node-internal packet transmission sequence, we envision an adaptation of the legacy 802.11 MAC functionality to enable an inter-node, benefit-based broadcast sequence. For this purpose, the dynamic adjustment of the so called contention window (CW) within the MAC layer is considered a major lever. Each station uses its individual CW to select both backoff and defer timers, which represent a key feature of the CSMA mechanism (see Fig. 2). During the transmission of a data packet, all stations except from the sending one only listen to the channel. After the transmission is finished, the stations that intend to broadcast a packet, start a so-called defer timer. Not until this timer has expired, they may start (or resume) counting down their backoff timers. The station whose timer expires first may then access the medium. The CW-size is initially set to CW_{min}, and is increased each time a transmission attempt fails with an upper limit of CW_{max}. In the case of a send error, another backoff is performed using the new CW-value. After each successful transmission, the CW-value is reset to CW_{min}. By selecting short contention windows in case a highly relevant packet requests access to the medium, the node's likelihood to win the contention process is increased. The smaller the CW, the shorter the timers defining the period of time after a node may try or retry to access the shared medium. Equ. 3 shows the modified, benefit-based computation of a backoff timer, whose starting integer value is randomly determined from a uniform distribution over the interval $[0, CW]$. The slottime's length is set to 16 µs as defined in the legacy IEEE 802.11 specification. CW_{bb} represents the node's current, benefit based CW. The calculation of CW_{bb} is conducted according to Equ. 3, where CW_{max} (1023 slots) and CW_{min} (31 slots) are the minimum and maximum CWs. Thus, the CW a node applies can always be adapted to the benefit ($ur \in [0, 1]$) of the currently handled message.

$$CW_{bb} = ((1 - u)) (CW_{max} - CW_{min})) + CW_{min} \tag{3}$$

Several refinements of this CW-based approach are thinkable, of which we present only two due to space restrictions:

Per-period timer adaptation and per-packet timer adaptation: Two different ways of modifying the legacy MAC functionality can be considered. First, one may consider starting backoff timers only once (per packet) and transfer remaining timer values (e.g. in case another node transmits on the channel) into the next so-called contention periods. In this case, timers are counting down until they expire and trigger their respective nodes' transmission. As a second possibility, the timers are newly set in each contention period according to the current CW-size. This ensures a total benefit-orientation of the medium access functionality: Not the time a packet has already been waiting for access to the shared medium, but solely its current benefit for the adjacent nodes defines its likelihood to get medium access.

802.11e QoS: The 802.11e standard [7] enables stations to differentiate traffic in a different way: all stations have several different packet queues available and sort traffic into them according to the relevance/priority determined by the application layer beforehand. Nodes can have up to eight queues of which each represents a different Access Category (AC), which is often also referred to as Traffic Category (TC). Each category is assigned a certain priority determining the degree of favoritism with respect to access to the shared, wireless medium. Please refer to [3,8] for simulative evaluations of leveraging this standard to introduce traffic differentiation in high load VANET scenarios.

4 Simulation Setup and Results

4.1 Simulation environment

To allow for an as realistic as possible simulation of message propagation in VANETs, we used the environment presented in [2]: The movement of network nodes is generated by the CARISMA road traffic simulator, which is a proprietary tool developed by the BMW Group. The traffic simulator is based on the so-called Krauss mobility model [9], which is well recognized and accounts for physical properties of the vehicles such as length, maximum acceleration, and deceleration. The simulator works on a time-discrete basis and updates vehicle positions and directions every second. CARISMA reads in data regarding geography of the scenario from so called ESRI-Shapefiles containing information about the street network of a scenario. For the exact simulation of data propagation in a VANET, we used and extended the Network Simulator 2 (ns2), which features a well validated implementation of the IEEE 802.11 specification that is crucial for our purposes, and also provides an adequate radio wave propagation model (Two Ray Ground Model). Effects such as shadowing due to building walls are taken into account by a simple line-of-sight model which has been introduced in [12]. Valuable hints on strengths and weaknesses of the ns2-specific implementation of the MAC layer can be found in [17,13,6]. Minor deviations from the IEEE specification within the ns2 implementation have been corrected. The scenario which has been used for all of the simulations is as follows: Within an area of 8 km^2, 300 wireless enabled vehicles (all of which are assumed to be able to detect potential hazards) are moving around. A communication range of 400 m has been applied. The simulation duration was set to 100 s. For every scenario 50 independent iterations have been conducted to avoid statistical aberrations. To simulate highly loaded network scenarios, the nodes can only access a bandwidth of 0.3 Mbit/s. This facilitates the simulation of highly loaded, large networks, while reducing the number of events in the simulator to a reasonable extent. The benefit function applied for estimating the benefit for the receivers ur comprises parameters such as Distance from Information Source, Message Age, Information Category, Latest Broadcast, Latest Reception, Expected News Value and can be studied in detail in [3]. Please also refer to this publication regarding the applied traffic pattern, which follows the widely accepted store-and-forward approach.

The benefit function applied for estimating the benefit for the receivers ur comprises the following parameters: Distance from Information Source (di, in m, with a maximum of 300 m), Message Age (ma, in s, with a maximum of 50 s), Information Category (ic, integer ID, between 1 and 10), Latest Broadcast (lb, in s, with a maximum of 50 s), Latest Reception (lr, in s, with a maximum of 50 s) and Expected News Value ($\hat{nv}$ that is 0 when the information is likely to be known by the recipients and 1 otherwise). The resulting relevance function is Eqn. 4. The function for determining receiver benefit values is Eqn. 5.

$$\widehat{ur} = \widehat{nv} \cdot \frac{2 \cdot \frac{300\text{ m} - di}{300\text{ m}} + 2 \cdot \frac{50\text{ s} - ma}{50\text{ s}} + 1 \cdot (10 - ic) + 1 \cdot \frac{lb}{50\text{ s}} + 1 \cdot \frac{lr}{50\text{ s}}}{7} \tag{4}$$

$$ur = nv \frac{2 \cdot \frac{300\text{ m} - di}{300\text{ m}} + 2 \cdot \frac{50\text{ s} - ma}{50\text{ s}} + 1 \cdot (10 - ic) + 1 \cdot \frac{lr}{50\text{ s}}}{6} \tag{5}$$

4.2 Simulation Results

Our approach modifies the medium access rules to provide a useful form of ”controlled unfairness”. Data that has been identified to provide high benefit to potential recipients is given preferential access to the medium. It will therefore gain faster access at the expense of the lower priority traffic. To investigate the impacts of adjusting contention windows in a highly loaded network, the following simulation has been run: Only two messages (stemming from two different applications) are being disseminated throughout the network according to an unrestricted store-and-forward scheme, where each node relays every message it has not seen before to all of its neighbors. As soon as a message is passed down from the packet queue to the MAC layer, the contention window (CW) of the respective node is adjusted according to the estimated benefit of the message.

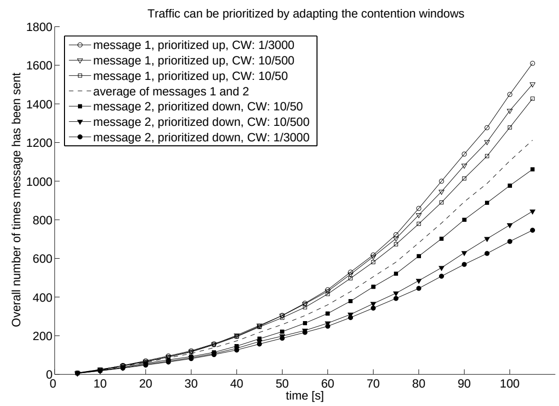


Fig. 3. Traffic differentiation due to adapted Contention Windows

As shown in Fig. 3, the propagation of messages has been examined with respect to three different parametrization: First, nodes sending a type-1 message apply a very small contention window of 1, where nodes intending to send a type-2 packet use a CW of 3000, which is an extreme application of unfairness with regard to medium access. Second, 10 (CW for type-1) and 500 (CW for type-2) have been used. Third, 10 (CW for type-1) and 50 (CW for type-2) were applied to introduce traffic differentiation, now showing smaller effect than with the first parameter set. In this high load scenario, the length of a node's CW significantly influences its likelihood to get access to the shared medium. In all three cases, type-1-messages reach nodes more quickly than without the prioritization, whereas type-2-messages are disseminated slower than in the conventional case. Last, the dashed line in the middle of the figure depicts the overall number of messages from both types sent in case traffic is not treated differently depending on its type.

As means for investigating the distribution of message benefit values, we chose the following simulation setup: On average, about 30 new data packets are generated each second and nodes have 0.3 Mbit/s of bandwidth available, where a simple, benefit agnostic store-and-forward mechanism for relaying the data has been applied in the first run. The packet queues at each of the nodes thus work according to the simple FIFO principle. Upon the reception of a message, each vehicle within the scenario starts a computation of the benefit received. The resulting values, combined with the current time stamps, are then logged in a file for evaluation. The results are depicted in Fig. 4, representing the outcome of only one simulation scenario. The plot shows that benefit values of packets shortly after the first packet transmissions are rather high. After some time has passed and messages have been propagated to a high number of vehicles with varying interest in information, many packets with very low benefit values are being

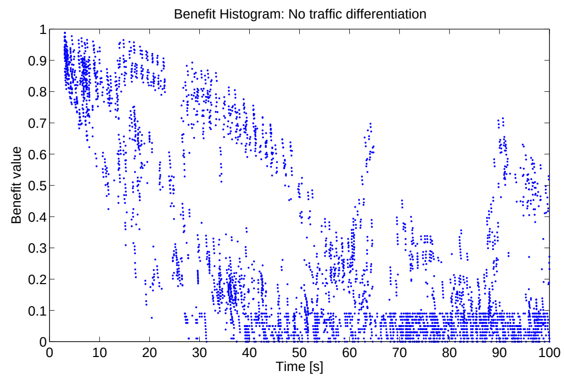


Fig. 4. Benefit value distribution in case of no traffic differentiation

received. Due to the lacking traffic differentiation based on data benefit, network resources are mainly absorbed by the transmission of low-benefit data packets. Only very rarely, new and highly relevant packets are granted access to the shared medium. A further effect can be inferred from this plot: Neighboring vehicles estimate the benefit of the same message rather similarly (see also in [3]). The numerous vertical chains of dots represent the reception of one certain message by a number of cars at the same point in time. With increasing network load over time, the benefit of the information received by the different vehicles decreases further. Network resources are wasted due to the transmission of more or less dispensable data, where highly relevant packets get stuck in the growing packets queues.

As a second step, we simulated the same scenario while applying a reorganization of the packet queues according to current packet benefit values. As can be seen in Fig. 5, the benefit of messages reaching the vehicles within the scenario can be significantly increased. Still, some messages with relatively low benefit values are received by the vehicles in the scenario, which can be put down to mainly three reasons: First, the benefit estimation within the cars may falsely evaluate the benefit a certain piece of information might provide to the adjacent nodes. Second, in case a node only has data with relatively low relevance available and its neighbors do not intend to send more relevant messages as well, messages with low benefit will get access to the medium. Third, no inter-node broadcast sequence has been established that ensures the node with the currently most relevant packet wins the medium contention process.

Finally, the MAC functionality has been additionally adapted: Instead of treating packets the same way and thus granting them the same chance to get access to the medium, we adapt the legacy CSMA mechanism such that defer- and backoff-timers are determined based on the benefit a packet is expected to provide to adjacent nodes. Also, timers are newly set each time the channel was sensed to be idle to guarantee an optimal alignment of packet benefit and channel access probability (per-period timer adaptation as briefly explained above. As visualized in Fig. 6, the benefit of the received packets could be improved even more. Due to the inter-vehicle coordination on

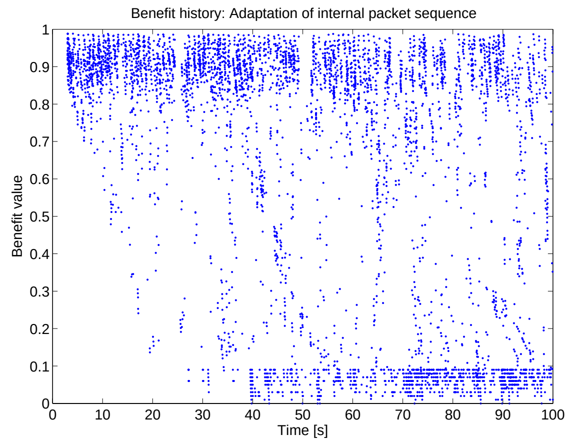


Fig. 5. Benefit value distribution in case of packet queue resort

the MAC-level, the delivery of highly relevant messages is ensured also in strongly overloaded networks, thereby contributing to the scalability of the whole system.

Our approach supports the efficient use of network resources in both sparse and dense networks with varying network nodes. It does not discard messages but adapts both node-internal and external broadcast sequence. Due to space restrictions, we do not include simulation results of scenarios with varying node density in this work.

Fig. 7(a) and Fig. 7(b) provide a comparison of the benefit values of received data packets for the three possible approaches (no differentiation, intra-node packet sequence modification and both intra- and inter-node broadcast sequence adaptation). The graphs show the accumulated number of successfully received packets for each of 20 benefit intervals between a maximum value of 1 and a minimum of 0. After 40 s of simulation time (Fig. 7(a)), one can already clearly see the advantages of adapting both internal packet sequence and MAC functionality to the packet benefit values. The delivery of highly relevant messages can be facilitated by differentiating the data traffic as described above. After 100 s, one recognizes a huge overall number of sent packets with low or even no benefit in all three case which results from the paradigm of not discarding, but delaying low-benefit information. We do not filter them out, but send them in case no high-benefit data requests for medium access. One side-effect of applying the MAC-layer traffic differentiation described above is an reduced overall data throughput. In case neither the packet broadcast sequence nor the MAC functionality is changed, 64371 packets have successfully been received on average during 100 s of simulation time. When applying the MAC adaptation, only 57002 packets have been received. This is due to the on average prolongation of backoff and defer timers. The legacy 802.11 standard foresees an initial CW-value of 31 slots. We apply starting values between 31 and 1023, depending on the packet's current expected benefit. Still, the overall network benefit is strongly improved due to the increased likelihood of highly relevant packets to get medium access.

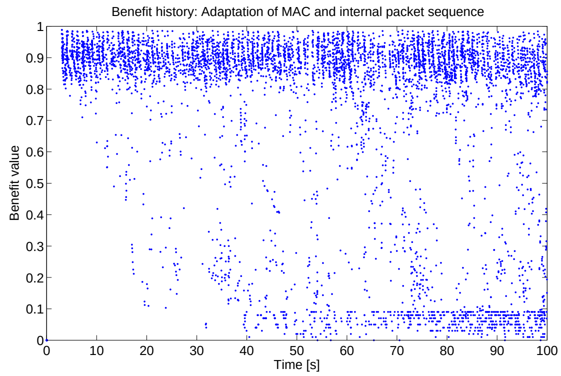
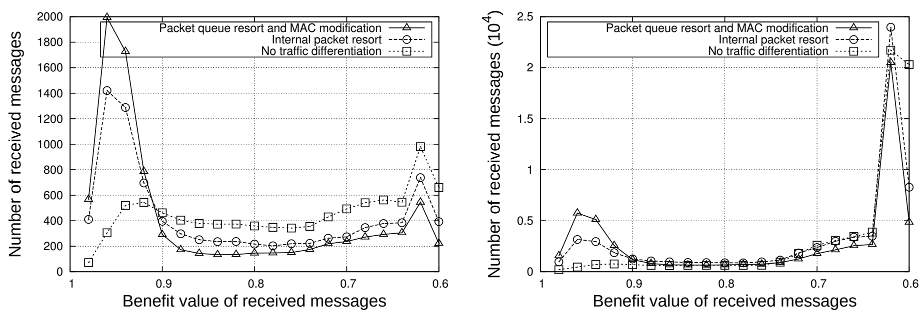


Fig. 6. Benefit value distribution in case of packet queue resort and MAC modification



(a) After 40 s simulation time

(b) After 100 s simulation time

Fig. 7. Benefit histograms

5 Conclusion

This work introduces a benefit-oriented, altruistic approach for information dissemination in VANETs. In contrast to the numerous existing techniques which solely aim at making broadcast-based data propagation more fast, reliable and efficient, we propose an integrated framework that allows for leveraging varying network resources as efficiently as possible and delivering information to where it is needed as fast as possible. Due to application-oriented data differentiation, we are able to take into account individual nodes' interests in information and transmit data accordingly. Broadcast sequence adaptation and different concepts for MAC modification have been proposed and evaluated by simulation, proving the adequacy of our approach for improving scalability of data dissemination in highly loaded VANET scenarios.

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