Chapter 12: Information Dissemination in Vehicular Networks

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Abstract

We discuss information dissemination principles in vehicular networks. In the early days of vehicular networking, many ideas investigated in the Mobile Ad Hoc Network (MANET) domain have been revisited for their applicability in what has been called a Vehicular Ad Hoc Network (VANET). The basis for many of these activities has been short range radio broadcast using IEEE 802.11b style protocols until its derivate for Inter-Vehicle Communication (IVC), IEEE 802.11p, had been standardized. It turned out that the topology of vehicular networks is way too dynamic to make this MANET approach a success. In turn, completely new concepts for information dissemination have been developed, ranging from one-hop broadcasting, which is better known as beaconing now, to geo-casting, and to using store-carry-forward concepts. At the same time, also the use of 3G and 4G cellular networks has been investigated. We review all these concepts and point out future trends in information dissemination.

Index Terms

None

CONTENTS

I. INTRODUCTION

This chapter investigates the state of the art in information dissemination in vehicular environments. In networking terminology we talk about the network layer, though certainly not in the traditional sense of one moving opaque blocks of data. Instead, vehicular networks are very much concerned with the actual information that is being exchanged, as we will explain. This topic is very broad in general and its history starts as early as that of Mobile Ad Hoc Networks (MANETs), which formed early approaches to information dissemination in vehicular networks. We decided to focus on the most recent concepts only that represent the current state of the art and build the basis for vehicular applications in the field.

Technology-wise, Wireless LAN (WLAN) based communication has been the first approach to Inter-Vehicle Communication (IVC). A major step forward towards IVC has been achieved with the standardization of the IEEE 802.11p protocol. Still, other communication technologies remain very important to the field, most prominently cellular networks now in the third or fourth generation. Both concepts, short range wireless communication and cellular networks, are complementary to each other. This also represents the conceptually logical next step in this field: heterogeneous networking.

Meanwhile, we see first large scale field operational tests all over the world. These testbeds help better understand limitations and shortcomings of current data dissemination schemes. It is therefore important to understand the reasoning behind modern dissemination schemes and, even more importantly, to see the directions in most recent approaches that may help define the next generation of communication schemes.

The chapter is covering the following aspects of information dissemination in vehicular networks:

- We start with a general discussion of information dissemination approaches in Section II. In this part, we develop an overview on the very different *concepts*. Based on this discussion, we pick selected approaches for in depth discussion in the following sections.
- In Section III, we discuss *broadcast-based dissemination* schemes. Current standardization of higher layers in the scope of Wireless Access in Vehicular Environments (WAVE) suggests periodic beaconing as a key function. This concept is explored in detail, also covering most recent congestion-aware concepts. Beaconing is the basis for cooperative awareness applications.
- *Multi-hop dissemination and store-carry-forward* is the logical extension of broadcasting concepts. In Section IV, we discuss most recent ideas including intelligent flooding and store-carry-forward concepts borrowed from Delay/Disruption Tolerant Networks (DTN). Applications widely range from emergency messaging to the exchange of traffic information.
- *Dissemination via cellular networks*, presented in Section V, is a completely different way of data dissemination and, as long as IEEE 802.11p is not fully deployed, the only realistic option for information exchange among vehicles. Communication concepts based on 3G/4G networks include distributed management of traffic information but also emergency notifications.
- We conclude the discussions with an outlook of upcoming trends for data dissemination in Section VI

and some recommendations for further reading in Section VII.

II. Dissemination Concepts

Data dissemination in vehicular networks has very different characteristics compared to other types of mobile networks [1]–[3]. This is mainly due to the inherent high degree of mobility but also due to other aspects contributing to the high dynamics in network connectivity, topology, and availability. As an example, the nature of radio shadowing caused by buildings and other vehicles should be named, which is strongly depending not only on the position of the vehicle but also those of other vehicles. In general, we can distinguish two classes of communication technologies that can be used for Inter-Vehicle Communication (IVC). First, direct radio communication using technologies such as WiFi or its specialized version in vehicular environments, Dedicated Short-Range Communication (DSRC), which has been standardized as IEEE 802.11p [4]. Upper layer protocols have become available in the Wireless Access in Vehicular Environments (WAVE) protocol suite. This allows to establish an ad hoc network similar to what has been investigated for a long time in the context of Mobile Ad Hoc Networks (MANETs). Secondly, cellular networks can be used for IVC, making use of the almost ubiquitously available cellular communication infrastructure [5]. As is usual, the truth lies in between: there is now a growing trend towards heterogeneous networks, i.e., the use of multiple networking technologies together to overcome limitations of the respective approaches [6].

Before we start discussing the individual concepts and proposed data dissemination concepts, we need to briefly investigate IVC applications and their requirements on communication channels. Figure 1 outlines a taxonomy: In general, we have to distinguish between safety and non-safety applications, both of which have different requirements mainly in terms of communication latency. Without going very much into the details, it seems to be rational to assume low latencies for DSRC, but better throughput for cellular networks. Strict limits to the applicability of the two are not well defined; range and cost will eventually determine their deployment.

In general, it can be said that short range broadcasting provides low latencies – yet, the scalability of multi-hop broadcasting remains unclear. As already mentioned, the initial idea was to adapt MANET algorithms. This approach coined the term Vehicular Ad Hoc Network (VANET) [2]. It quickly turned out that this approach is infeasible in general. The main problem being that MANET routing techniques are based on topology management that becomes very problematic if the topology changes too quickly. For example, in [7] the authors investigated in detail the use of the routing protocol Dynamic MANET on Demand (DYMO) in vehicular environments and discovered that the correct configuration strongly depends on the vehicles' density – a parameter that cannot be changed easily at run time.

This problem has been dealt with by proposing concepts that are able to handle the problem of disconnections [8], [9]. The idea is borrowed from classical Delay/Disruption Tolerant Network (DTN) routing. Messages are forwarded according to the store-carry-forward concept, exploiting the vehicles' mobility: a message can be carried by one car until it meets another to bridge communication gaps.

A second concept that has been investigated in detail is the use of the geographic positions of communicating vehicles to disseminate messages [10]. This geo-routing idea allows to send messages exactly into the right direction – a consequent property of it being delivered not in a communication network but in a road network [11], [12].

The mentioned dissemination concepts are rather similar to what has previously been investigated in the field of MANETs. One concept that has been envisioned already in the very first days of inter-vehicle communication and which is unique to this field is *beaconing*. Beaconing, i.e., simple one-hop broadcasting, allows to exchange information between neighboring vehicles in a very efficient manner. It has first been used in the context of the Self-Organizing Traffic Information System (SOTIS) approach, which is also one of the first concepts of a fully distributed traffic information system [13]. The idea of simple periodic beacons has also been considered in the first days of standardization efforts towards data dissemination in vehicular networks [14]. This, of course, leads to problems (again) if the vehicles' density changes – as is typically to be expected if looking at different times of a day (sparse at night time, dense in rush hours) or at different locations (suburban vs. urban vs. freeway). To handle all situations, new solutions have been developed by making the beacon interval adaptive. One of the first approaches in this direction has been the Adaptive Traffic Beacon (ATB) protocol [15]. The protocol estimates the quality of the wireless communication channel and uses this metric, together with some priority of the data to be disseminated, to adapt the beaconing interval. This adaptive approach has then be adopted by the ETSI standardization efforts. Congestion control became one of the major requirements [16].

At the same time, the use of cellular networks has been investigated. Besides the obvious use for accessing Internet services as implemented in navigation units and smart phones, also the direct communication between vehicles can be supported by cellular networks. This is rather obvious if non-safety applications such as traffic information systems are concerned, a good example being the Peer-to-Peer Traffic Information System (PeerTIS) approach [17], but it becomes more complicated if the limits are to be pushed towards safety applications. This has been studied, for example, in the CoCar project, the core outcome being that – if dedicated services can be deployed at critical places in the operator's core network and if a multicast service such as Multimedia Broadcast/Multicast Service (MBMS) is available – low-latency emergency messages become at least feasible [5].

Altogether, (geo-)routing concepts, DTN concepts, beaconing, and cellular networks represent techniques for data dissemination on which vehicular networking can be built. Of course, more sophisticated broadcasting schemes considering fairness, congestion control, and scalability of wide area information dissemination [18], as well as more complex DTN solutions taking into account the complex environment need to be investigated.

III. Broadcast-based Dissemination

In this section, we study broadcast-based dissemination schemes, i.e., beaconing, in more detail. We start looking at the early simple or static beaconing concept before we investigate more sophisticated adaptive solutions.

A. Simple Beaconing

Discussing simple beaconing concepts requires some basic knowledge about the used access technologies. Thanks to recent standardization efforts, we can now rely on full communication stacks, which are available for direct data dissemination between vehicles and vehicles and infrastructure elements such as Roadside Units (RSUs). These standards are the U.S. WAVE and the European ITS G5. The heart of both is IEEE 802.11p, which defines the physical and the MAC layers [4]. Conceptually, IEEE 802.11p combines IEEE 802.11a and IEEE 802.11e, and internally changes the timings and channel bandwidth (now 10 MHz) to cope with channel conditions of vehicular networks. Most of the dissemination schemes discussed in this chapter build upon this standard.

The WAVE stack adds higher layer functionality in the context of a family of standards comprising, for example, the SAE J2735 DSRC Message Set Dictionary [19] defining application layer protocols, IEEE 1609.3 [20] for network and transport layers, and IEEE 1609.4 [21] for operation on more than one radio channel. WAVE supports, depending on the region, 5 to 7 channels, one dedicated as a Control Channel (CCH) for channel management and safety messages, the others marked as Service Channel (SCH) for general data dissemination. For channel coordination, WAVE defines two types of main messages: Wave Service Announcement (WSA) and Wave Short Message (WSM). WSAs are used to announce upcoming WSMs to be sent on a selected SCH in the next time interval. Channel management is not specified by WAVE. It is up to the application to make use of these concepts.

ETSI ITS G5 defines a more complex networking stack, integrating some of the advances introduced in this chapter like channel access control and multi hop geo-networking. It is built with two very different types of messages for direct data dissemination between vehicles in mind:

- Decentralized Environmental Notification Messages (DENMs) have been suggested for event driven (safety) messages that are only sent as needed and that are designed for distribution over multiple hops. We will discuss multi hop message transport in Section IV.
- Cooperative Awareness Messages (CAMs) – closely resembling Basic Safety Messages (BSMs) in SAE J2735 – are used for beaconing of situation awareness data. This facility builds the basis for many others that need to take one-hop neighborship information into account.

Initial proposals for static beaconing allocated fixed beaconing rates in the range of 1 Hz to 10 Hz, which has later been extended to up to 40 Hz for safety applications. This means that, depending on the environment, the system would either be prone to overload the channel, or heavily under-utilize wireless resources. This changed with the introduction of adaptive mechanisms as we will show in the following.

B. Adaptive Beaconing

The Adaptive Traffic Beacon (ATB) protocol addressed the shortcomings of periodic beaconing with a fixed interval [15], [22]. Intuitively, it simply manages the beacon interval to prevent congestion in very crowded networks and still supports low latency transmissions for urgent messages. ATB achieves this by employing two different metrics, the *channel quality* C and the *message utility* P, to calculate the beacon interval I with which to disseminate messages:

- The channel quality C is estimated by means of three metrics, which are indicative of network conditions in the past, present, and future, respectively. First, a node observes the number of collisions on the channel, deriving a value K which is a measure of past channel conditions. ATB is very sensitive to this metric to prevent overload situations. Secondly, a node continuously measures the Signal to Interference and Noise Ratio (SINR) on the channel to derive S, which reflects current channel use. Obviously, this is only an indicator for the channel quality. If the SINR is low, i.e., either the received power is low or the interference and noise level is high, a larger beacon interval is beneficial as this gives those cars priority access to the channel that are better connected. This is in line with findings published, for example, in [23]. Lastly, a node observes other nodes' beacons, deriving a measure for the number of neighbors N and thus enabling it to factor in, to a certain degree, the outcome of channel access in the near future.
- The message utility P is derived from two metrics. First, a node accounts for the distance of a vehicle to an event as D_e, which is the most direct indication of message utility. Secondly, it accounts for message age A, thus allowing newer information to spread faster. Both D_e and A are of equal value for determining the compound utility metric P.

C and P range from 0 to 1, lower values describing a better channel quality or higher priority messages, respectively. Detailed information on the calculation of C and P is given in [22], which also details further adaptations to incorporate how useful a particular message might be in the presence of RSUs, as well as its utility to nearby RSUs.

Based on the presented metrics, ATB continuously adapts the beacon interval I in a range from I_{min} to I_{max}. ATB adjusts I such that it becomes minimal only for the highest message utility and the best channel quality. In all other cases, channel use is reduced drastically, allowing uninterrupted use of the channel by other applications:

$$I = I_{min} + \left(I_{max} - I_{min}\right) \times \left(w_I C^2 + (1 - w_I) P^2\right) \tag{1}$$

The relative impact of parameter w_I is designed to be configurable, e.g., in order to calibrate ATB for different MAC protocols. Based on empirical data, the factor of $w_I = 0.75$ turned out to be most useful, i.e., weighting the channel quality higher than the message priority. That means that the beacon interval is very sensitive to the conditions of the radio channel.

As the channel quality metric C in turn depends on the value of I that was chosen by nearby vehicles, ATB exhibits some properties of a *self-organizing system* [24]: on a macroscopic scale, vehicles participating in the VANET will independently arrive at beacon intervals that enable them to use the shared channel commensurate to their own and other nodes' needs. Hence, proper rules at the local level (car level) lead to emergent behavior at the global level.

The graphs in Figure 2 outline some of the advantages of ATB compared to static beaconing. The results were taken from a large simulation experiment in an Manhattan grid scenario (cf. [15]). As can be seen in Figure 2a, the delay of an emergency message transmitted besides the normal cooperative awareness messages, obviously, depends on the beaconing interval. The larger the beacon interval, the larger the delay. The results also indicate that ATB was able to transmit an emergency message even faster than was possible using a fixed beacon interval of 30 ms, which was also used for the minimum beacon interval of ATB.

This effect can be explained when looking at the level of congestion in the wireless network. As can be seen from Figure 2b, which depicts the number of collisions observed on the channel per packet received in a log-scale graph, the load caused by the static beaconing increases exponentially for smaller periods. In contrast, ATB is able to perform well in all the investigated scenarios. Thus, we can conclude that ATB succeeds at managing access to the radio channel – which, according to the used quality metrics, also holds if other devices or applications start sharing the same wireless channel.

Similar approaches to adaptive beaconing have been published in the literature, all focusing on carefully adapting the beacon interval in order not to overload the wireless channel [25]–[28].

C. Towards a Next Generation of Beaconing Systems

The concept of adaptive beacon intervals eventually found its way into current standardization efforts, in particular ETSI ITS G5. In order to not overload the channel its Decentralized Congestion Control (DCC) access control mechanism takes care to limit the transmission rate, power, modulation etc. of messages [16]. It was shown [29] that the most successful control strategy adapts transmit power to the target distance (the maximum distance to interested vehicles in one-hop range) and uses Transmit Rate Control (TRC) to adapt to channel load. As the target distance is unknown for undirected dissemination, TRC is the mechanism of choice for beaconing systems.

TRC measures the busy fraction b_r of the wireless channel, i.e., the time used for sending messages compared to the observation time (e.g., 1 s). The idea is to change the protocol behavior according to the measured busy fraction b_r. If the channel is close to saturation, the beaconing frequency is reduced; if the channel is idle, the beaconing frequency can be increased. For this, DCC TRC maintains a state machine that assigns one of three basic states to the channel: relaxed, active, or restricted (cf. Figure 3). For the *active* state, any of a number of different sub-states (4 for the service channels, none for the control channel) is selected if channel conditions change. Switching between states is done by checking $b_{\mathrm{min},1\,\mathrm{s}}$, the minimal value of b_r in the past second and $b_{\max,5\,\mathrm{s}}$, the maximal value of b_r in the past five seconds then changing states as outlined in Figure 3.

In a static scenario, the TRC scheme was shown to successfully manage channel access, albeit at the cost of synchronized oscillations in channel load and a pronounced under-utilization of channel capacity [30]. Moreover, in highly dynamic scenarios the algorithm can also lead to the opposite: a pronounced over-utilization of channel capacity and, thus, packet loss. Reasons for these problems can be easily found in its poor adaptation properties and a coarse design of the controlling algorithm.

Based on these observations, a novel, more sophisticated and theoretically sound adaptation algorithm, named Dynamic Beaconing (DynB), has been proposed [31]. In a first step, all the additional sampling and windowing parameters have been removed for two reasons. First, control theory shows that, in a sampled system, using sampling processes different from the fundamental one can lead to the mentioned instabilities. Second, the beacons themselves offer a natural and very convenient sampling process.

DynB uses only two control variables: b_r (the fraction of busy time between $t - I$ and t) and N (the simple one-hop neighbor count). These variables are used to force the beacon interval I as close as possible to a desired value I_{des} as long as the channel load does not exceed a desired value b_{des}. Let $r = b_r/b_{\mathrm{des}} - 1$, clipped in $[0, 1]$, be a measure of the distance by which the actual channel load b_t exceeds a desired load b_{des}. The beacon interval can now be calculated as

$$I = I_{\mathrm{des}}\,(1 + rN)\,.$$

The rationale is as follows: I should increase as the network becomes denser (more neighbors), and it must do so only when the channel occupancy is above the target value. The algorithm is fully distributed and each node adapts its beaconing interval to the local conditions. Computing N is trivial, as a neighbor is defined as a node j whose beacons are received at node i, so a good estimate of N is simply the number of nodes whose beacons have been received in the time interval $I_{\max}$.

As the impact of collisions on safety applications is catastrophic, the channel load needs to be maintained at a level that guarantees a marginal collision rate, let's say $p_{\mathrm{coll}} \leq 0.05$. Disregarding the backoff freezing on successive attempts, we can approximate it with the probability that two or more stations have a beacon to transmit while the channel is busy multiplied by the probability that at least two stations chose the same backoff within the contention window. Easy combinatorics (not reported here for the sake of brevity) leads to a desired channel busy ratio of $b_{\mathrm{des}} = 0.25$ for values of N compatible with vehicular networks [31].

DynB was shown to be stable under heavy network congestion, and to be able to quickly react to density changes; the remaining question is if the proposed concept is really able to deal with extremely dynamic changes in the environment. For this, the following experiment covering an extreme case of topology change has been conducted: Two clusters of 100 nodes each, both fully meshed, were kept separate until their beaconing rates stabilized. Then, both clusters were put into contact to meet for 5 s before they departed from each other again. Figure 4 shows for both TRC and DynB that both algorithms successfully and dynamically choose the beacon interval according to changes in the number of neighbors. TRC reacts less spontaneously compared to DynB and also overestimates the channel use. DynB reacts almost instantly to the changes and with only a minimal increase in the beacon interval. As TRC averages the measurements over time, this leads to a pronounced delay until it can react to changes in network topology. In contrast, DynB reacts very aggressively; no over- or underestimation of the change in network topology can be observed; the adaptation is almost instant.

Not mentioned so far is the need to achieve more fairness in the beaconing concepts. As this is entirely a self-organizing, fully distributed process, it needs to be ensured that all vehicles get the same (fair) share of the wireless channel capacity. First studies already show promising results, most notably the FairDD [32] and FairAD [33], [34] solutions.

IV. Multi-Hop Dissemination and Store-Carry-Forward

If data needs to be disseminated over multiple hops, and simple re-broadcasting is no option, two conceptually orthogonal concepts can be used: (intelligent) flooding, potentially combined with directed dissemination based on geographical positions, and the *store-carry-forward* concept known from Delay/Disruption Tolerant Networks (DTN). In this section, we explore both concepts using some well-established examples.

A. Intelligent Flooding and Geo-Casting

The most simple concept to disseminate information to all other vehicles is to flood the data, i.e., to send to all neighbors and to repeat this process until all vehicles received the information. This procedure quickly leads to what is known as the broadcast storm problem [35], [36]. Two concepts have been investigated to overcome this problem: broadcast suppression and geo-casting. Both techniques can also be used in combination.

The general idea of broadcast suppression is to select best candidates among all vehicles that might be able to forward the message. All other nodes overhearing the forwarded message are supposed to cancel (to suppress) their re-broadcast. In the literature, several schemes have been proposed for this broadcast suppression, for example weighted p-persistence, slotted 1-persistence and slotted p-persistence [23], [36]. The idea of these approaches is rather simple: The common idea is to greedily make progress in all directions. This is achieved by preferring the vehicles most far away from the source node. Figure 5 outlines the concept. In particular, weighted p-persistence maintains probabilities p as a function of the distance to the source. This may lead to unnecessary collisions as two nodes might select very close re-transmission times. Slotted 1-persistence addresses this by managing time slots that are assigned according to the distance to the sender. The idea is to assign the shortest delay to the vehicles farthest away from the sender. This way, even spatial re-use of the channel is possible as vehicles at opposite sides of the sender may re-broadcast at the same time (given the distance is big enough). Finally, slotted p-persistence mixes probability and delay by giving vehicles with highest priority the shortest delay and highest probability to rebroadcast.

As already pointed out in early work on vehicular networks, location-based routing can help overcoming problems due to the dynamic nature of such networks [10]. This principle, i.e., to forward data only to a certain position or area, has practical applications and may also help solving the broadcast storm problem more effectively, given that some data, e.g., notification about a critical accident or very generic parking place information, is only relevant to cars following or those driving to a certain place. This concept, called geo-casting, has been already explored in the scope of MANETs [37]. Geo-routing concepts also help "looking around the corner", e.g., if signals are obstructed due to shadowing and a two-hop broadcast can help sending the message to the final destination [12].

Geo-casting can directly be combined with the flooding concept. There is no need to forward messages any further if no progress towards a destination location or area can be achieved. ETSI standardization picked up this idea to combine situation awareness beaconing with geo-casting concepts in ITS G5 [38].

B. Store-Carry-Forward

Vehicular networks represent a class of intermittently connected networks, which makes it hard to provide end-to-end connectivity by any means of IVC. This is also a main reason why the flooding approach has only limited performance considering coverage as the main metric. This problem has been investigated in detail in the field of Delay/Disruption Tolerant Networks (DTN) [9], [39]. The idea is to use the store-carry-forward communication principle exploiting spontaneous contacts between mobile systems to disseminate information in an epidemic manner [40].

One of the first approaches making full use of this idea by combining flooding based dissemination with store-carry-forward has been Distributed Vehicular Broadcast (DV-CAST) [23]. DV-CAST switches between these two operation modes (flooding and store-carry-forward) depending on the density of the vehicles as known to the sender. If there are no potential forwarders in the backward direction on a freeway, DV-CAST tries to use vehicles driving in the opposite direction. This concept is depicted in Figure 6. As can be seen, three groups (or clusters) of cars are driving on a freeway. Let us assume that the leader of group 1 starts to disseminate a message. Groups 1 and 2 are disconnected. The only possible communication alternative, and the one chosen by DV-CAST, is to use vehicles in group 3 to carry information from group 1 to group 2. This way, communication becomes more efficient in terms of coverage but, of course, transmission latencies become unpredictable.

V. Dissemination via Cellular Networks

In this section, we discuss how cellular networks such as UMTS (3G) or LTE (4G) can be used for data dissemination between vehicles. The typical Internet-based access to centralized resources is not considered in this discussion as this is not very different compared to other applications scenarios. In general, we have to distinguish between two, conceptually very different approaches: The first one is to use the full cellular network for connections between arbitrary cars that are not necessarily connected to the same base station.

The key problem is to manage the addresses of the destinations without any centralized resources. The second option is to only use a wireless broadcasting option in a local cell to send to all neighboring vehicles.

A. PeerTIS

Data dissemination for building a large scale fully distributed traffic information system based on cellular networks has been investigated for example in the scope of the Peer-to-Peer Traffic Information System (PeerTIS) [17]. The concept is based on that of Distributed Hash Tables (DHTs). Internet-based DHTs such as Chord [41] and Content Addressable Networks (CANs) [42] provide efficient distributed storage over a large number of nodes in IP-based networks [43].

PeerTIS' motivation is that traffic information systems need to keep data current with high spatial resolution. This can easily be achieved, given we ignore any performance bottlenecks, in a quasi-static and well-connected network. Doing this in a fully distributed manner in intermittently connected networks complicates the situation as there is usually no random access to all stored data. Instead, locality of data potentially penalizes a few systems but can also be exploited for efficient access as follows. The idea is to store all data in a typical DHT. The developers of PeerTIS selected CAN for this purpose. All members of the DHT manage traffic information that is associated to a part of the overall map, i.e., each vehicle needs to be responsible for a certain tile of the map. This association is managed in the join and leave process. Joining a PeerTIS network means that any node's key space will be split into two parts. The joining vehicle takes over half of the data and becomes responsible for all further information related to this part of the map. The general idea is outlined in Figure 7.

If an unmodified DHT algorithm is used, the employed hashing most likely leads to random distribution of data (cf. Figure 7a). This, in turn, leads to long query times and high load in the network for subsequent queries. Internet-based DHTs are designed to cope with dynamic membership changes (node join/leave), and yet, they generally assume that the underlying physical network topology is quasi-static. PeerTIS exploits the direct relationship between the underlying map and the associated data. The idea is to use CAN, but to replace the hashing algorithm with neighborship information according to the underlying map. Physical neighbors become responsible for neighboring areas, which allows for faster lookup of information close by. As shown in Figure 7b, this optimization results in simple one-hop forwarding of queries to collect all traffic information related to a planned route. Additional optimizations are possible, e.g., by exploiting time correlation of queries (initial query, then periodic updates), and by exploiting spatial distribution of nodes (instead of assigning random geographic areas to nodes, an area close to their start of route are used).

B. Cellular Multicast

The use of 3G and 4G networks for vehicular networks has been investigated in several studies involving all the major stake holders in this domain [5], [44], [45]. Cellular networks of the third (3G) and fourth generation (4G) such as UMTS, LTE, and LTE Advanced not only support unicast communication, but also what is called cellular multicast. This Multimedia Broadcast/Multicast Service (MBMS) technique basically allows to flexibly create and maintain multicast sessions.

This concept has, for example, been investigated in detail in the scope of the CoCar project for UMTS [5]. Figure 8a depicts an overview of the CoCar communication system, along with the various models that have been integrated to form the testbed that has been used for evaluations. As can be seen, delay sensitive short range dissemination of data in envisioned to take place via a dedicated component in each cell, called the CoCar reflector. These Fast Traffic Alert Protocol (FTAP) messages are sent in a very compact, binary representation. In the downlink, these messages are quickly broadcast to all vehicles in the same cell, again using the FTAP protocol. Wide area dissemination is coordinated by a central aggregator, essentially a traffic information center, and executed via geo-cast managers. These messages sent from the traffic information center are using a message format based on that of the Transport Protocol Expert Group (TPEG) protocol suite, which defines a standardized means of traffic data exchange between cooperating parties and with end users. CoCar messages were integrated with this suite, specifying missing CoCar information elements to form a TPEG-conformant message type, called an *application* in TPEG terminology.

In the CoCar project, both options for downstream information dissemination have been explored – unicast and multicast. Simulation results presented in [5] have been conducted for a typical highway scenario, based on real-world 3G network coverage data. Figure 8b shows the performance of MBMS compared to unicast communication within the same cell. Focusing on the single use case of traffic jam warning exchange, it has been shown that MBMS supports low latency communication with delays around 120 ms compared to 350 ms in the unicast case. Latencies for the centralized approach are even higher and mainly depend on load in the core network and the centralized server.

VI. Future Trends

Information dissemination concepts in vehicular networks have seen major changes in the last decade. This was mainly caused by the need to adjust to the specific structure and behavior of VANETs. The different techniques have now been explored to a great level of detail. In September 2013, some of the leading experts in the field met for a second time for a Dagstuhl Seminar, an internationally renowned seminar series, to discuss the future of Inter-Vehicle Communication (the outcomes of the meetings have been published in [46], [47]). The seminar war co-organized by the authors of this chapter. The participants concluded that, on the one hand, information dissemination schemes are mature enough to see first deployments. On the other hand, they also identified several challenges that need further research and investigation.

In the following, we list selected open research questions:

- *Congestion control* is needed in general in order not to overload the wireless channel. After initial approaches to solve the problem (e.g., in the scope of the ATB protocol development [22]), this need has also been identified by standardization bodies, who most recently defined the Decentralized Congestion

Control (DCC) concept [16]. Yet, more aggressive protocols such as DynB [31] are needed to keep track with the extreme dynamics in vehicular networks.

- *Fairness* has been one of the major requirements in most communication networks. The idea is to ensure that each vehicle gets a fair share of the wireless network capacity. As beaconing is inherently a fully distributed, self-organizing process, fairness needs to be carefully ensured in the protocol design [32]. At the same time, congestion control and prioritization for safety related emergency messages need to be provided. New concepts integrating fairness in all IVC techniques are needed, FairAD [34] being a promising first step.
- *Multi channel operation* promises to linearly increase the capacity of the wireless network by using additional channels as defined in the WAVE standard. It is a well-known fact that this linear increase only holds in theory. Channel management induces a non-negligible overhead that needs to be investigated. First studies on multi-channel beaconing already show promising results [48], but need to be further investigated to allow a better use of the spectrum.
- *Integration with geo-casting* for multi-hop dissemination is potentially the only option for directing messages to a certain position or area. Current approaches have not yet solved the problem of extremely high mobility. As network topology dynamics are rather predictable on our streets, concepts can be developed to particularly send messages around a corner [12] or simply weakening the broadcast storm problem by disseminating into a single direction (cf. standardization efforts towards geo-casting [38]).
- *Application awareness* of information dissemination protocols has not yet been considered as a key characteristic of developed protocols. Either the protocols have been created for a single application only, or they are so generic that specific application demands cannot be fulfilled. Yet, applications such as platooning [49] (the most extreme form of cooperative driving) might need careful transmit power control to manage the communication between subsequent vehicles in the platoon, or intersection safety applications have to be able to configure the beaconing rate according to the current level of criticality during the intersection approach [50].
- *Heterogeneous networking* has been identified as the key solution to overcome a low penetration in the market after initial deployment of DSRC/WAVE based radios. To distribute the load better between cellular networks providing a constant high data rate link, Wi-Fi access points for periodic Internet access, and DSRC/WAVE for critical low-latency application, we need to rely on the right technology at the right time. It may even help using all technologies at the same time for life critical safety operations. First approaches towards heterogeneous networking have been investigated [6], but this is still a rather unexplored area.

VII. Further reading

The vehicular networking community initiated several international workshops since early 2000. Some of the major workshops have been merged into what has become the key conference in the field, which is fully sponsored by IEEE Communications Society and IEEE Vehicular Technology Society:

- IEEE Vehicular Networking Conference (VNC), annual conference since 2009

One of the leading workshops in the field, ACM VANET, should to be mentioned explicitly as it helped to a great extent to form the community working on information dissemination in vehicular networks. After the IEEE VNC conference became established, ACM VANET is now considered to be concluded.

In the course that vehicular networking became one of the central domains in networking, all major networking conferences feature vehicular networking related tracks or sessions.

A research oriented meeting has been organized in form of a Dagstuhl seminar series at the internationally renowned center for computer science related seminars, Dagstuhl castle. The most recent seminar just took place in September 2013:

- Dagstuhl Seminar 10402 on Inter-Vehicular Communication, October 2010, research directions published in [46]
- Dagstuhl Seminar 13392 Inter-Vehicular Communication - Quo Vadis, September 2013, research directions published in [47]

Besides the many journals and magazines related to wireless networking and communications that also feature special issues on inter-vehicle communication, one periodical needs to be mentioned particularly focusing on IVC:

- Automotive Series in IEEE Communications Magazine, appearing twice a year

Books covering the topic of Inter-Vehicle Communication include the following edited books

- Hannes Hartenstein and Kenneth Laberteaux, VANET - Vehicular Applications and Inter-Networking Technologies, in Intelligent Transport Systems, Chichester: John Wiley & Sons, 2010
- Stephan Olariu and Michele C. Weigle, Vehicular Networks - From Theory to Practice, Boca Raton, London, New York: CRC Press, Taylor and Francis, 2009

and one textbook that will appear in 2014

- Christoph Sommer and Falko Dressler, Vehicular Networking, Cambridge University Press

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List of Figures

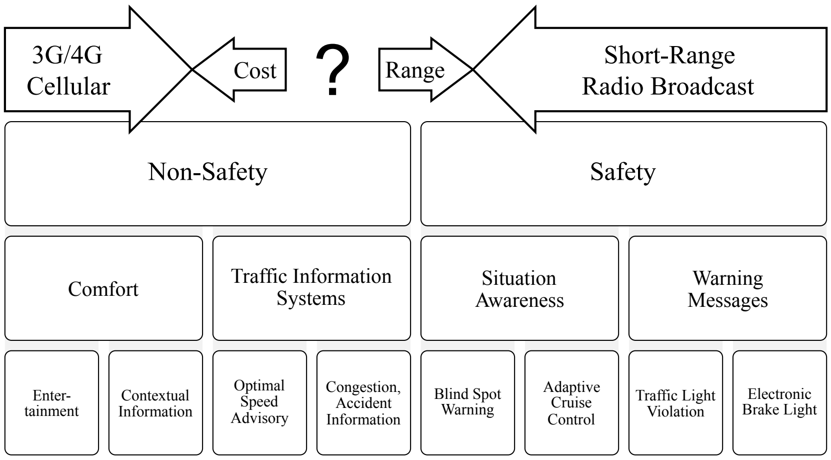
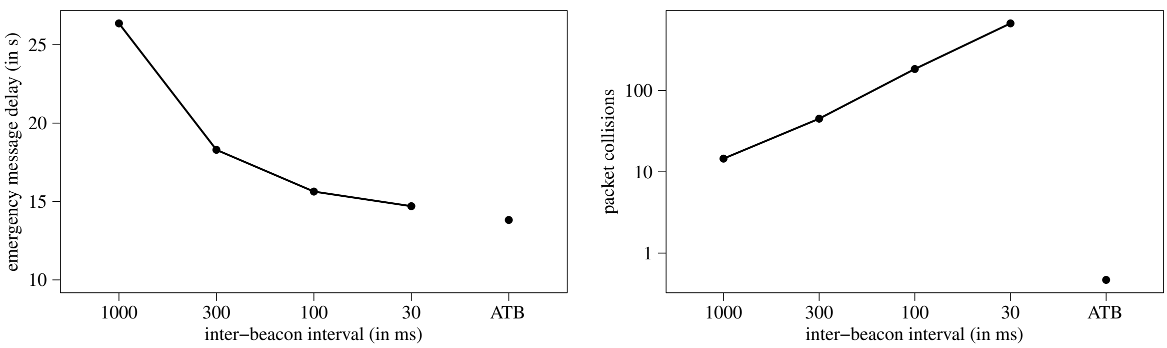


Figure 1. Taxonomy of IVC applications and technologies



(a) mean delay of a high-priority message

(b) MAC layer collisions

Figure 2. Beaconing performance metrics recorded in the $16\,\mathrm{km}^2$ grid scenario for various fixed beacon intervals as well as for ATB (for details of the simulation setup, please refer to [15]).

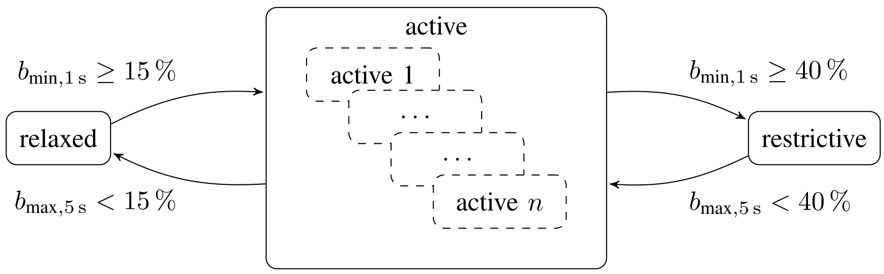


Figure 3. ETSI ITS G5 DCC state machine.

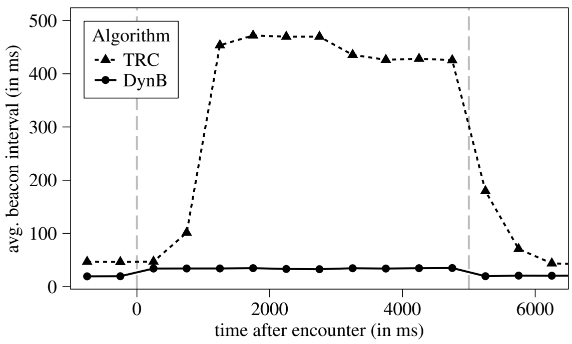


Figure 4. Comparison of the mean beacon intervals calculated by TRC and DynB when two initially disconnected clusters of vehicles meet (at time 0) and separate again (5000 ms later). For details of the simulation setup, please refer to [31].

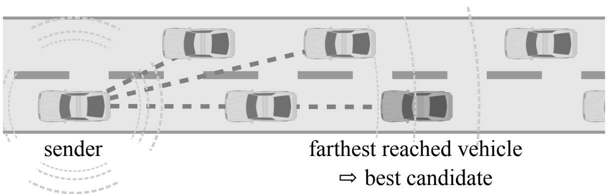


Figure 5. Conceptual idea of broadcast suppression using slotted 1-persistence.

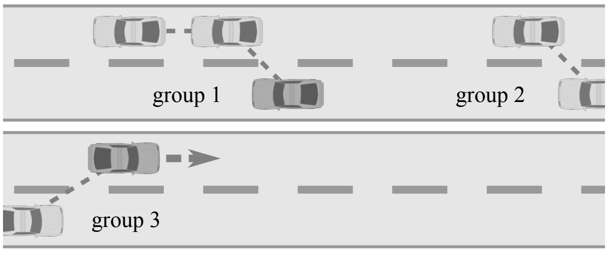
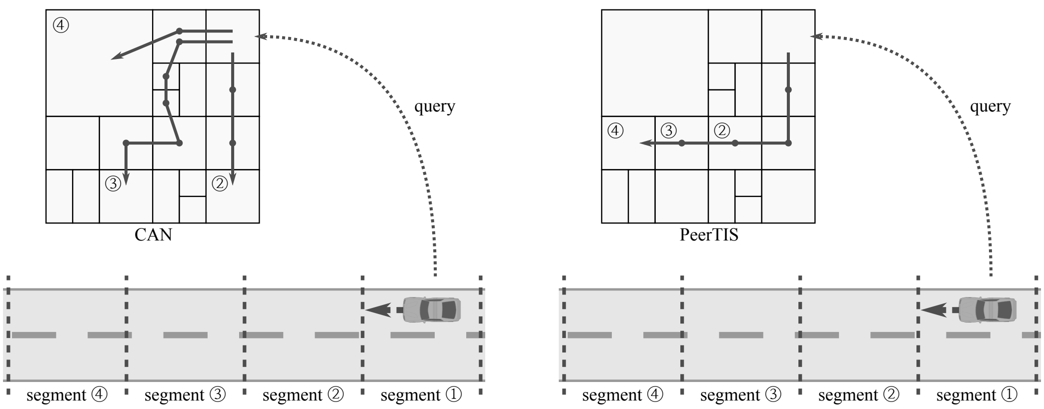


Figure 6. Principle of store-carry-forward between clusters of vehicles on a freeway.



(a) Unmodified DHT algorithm.

(b) Improved DHT for TIS.

Figure 7. PeerTIS approach to store traffic information in the form of a DHT on vehicles participating in the system.

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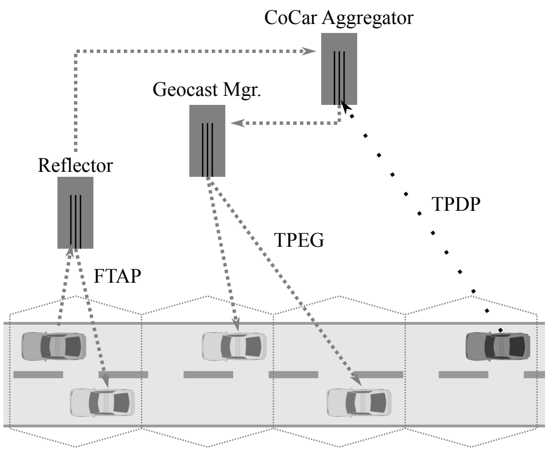
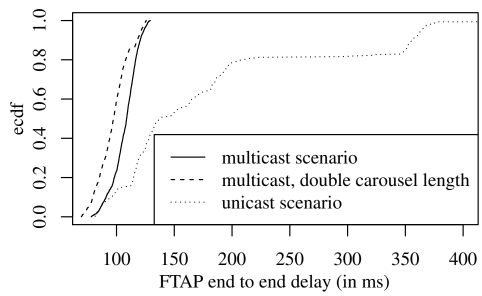


(a) Communication principles in 3G/4G networks.



(b) Performance of MBMS based dissemination in UMTS networks.

Figure 8. CoCar communication architecture and performance (for details about the system and of the simulation setup, please refer to [5]).