On the nature of Inter-Vehicle Communication

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Abstract. In this position paper we argue that applications for the communication between vehicles do not require the functionality typically offered by mobile ad-hoc-networks or wireless sensor networks. Consequently the name Vehicular Ad-Hoc Network (VANET) is a misnomer leading practitioners and researchers astray. In order to make our point we briefly outline the characteristics of Mobile Ad-Hoc Networks (MANETs), wireless sensor networks and classical infrastructure-based access networks. We then show that the applications considered for car-to-car communication are best served either by the latter or require altogether different network services not found in mobile ad-hoc networks or Wireless Sensor Networks (WSNs). We conclude our statement by pointing out some of the fundamental and unique research challenges posed by Inter-Vehicle Communication (IVC).

1 Introduction

Enabling cars to exchange information about road conditions, traffic jams or emergency situations has the potential to improve road safety, efficiency and driving comfort. Inter-vehicle communication has therefore received significant attention especially from the ad-hoc networking community as one prime application area for mobile ad-hoc networks. In this context routing protocols have been modified and tested to cope with vehicular mobility patterns, roadside gateways were investigated as a means of Internet access, and medium access mechanisms have been developed to support multi-hop car-to-car communication. These efforts led to the establishment of the term Vehicular Ad-Hoc Network.

In this position paper we argue that the applications envisioned for inter-vehicle communication do not require the unicast and multicast services offered by Mobile Ad-Hoc Networks. As a consequence, the term VANET is a misnomer that can lead researchers astray as it suggests a too close relation to MANETs. Furthermore we reason that the basic functionality of wireless sensor networks is equally unsuited to support these applications. Inter-vehicle communication thus requires a set of new, unique network functionalities rather than an adaptation of existing network technology. The aim of this paper is to stimulate a discussion about the real problems that need to be tackled for inter-vehicle communication.

The remainder of this position statement is structured as follows. Section 2 summarizes the characteristics of mobile ad-hoc networks, sensor networks and infrastructure-based networks. In the third section we discuss common application classes of inter-vehicle communication and show that the characteristics of currently existing networking paradigms do not match their requirements. In Section 4 we investigate issues that are unique to inter-vehicle communication. The paper concludes with an overview of open research challenges.

2 Existing communication paradigms

This section lists existing communication paradigms related to car-to-car communication either because they provide network connectivity to mobile users or support distributed wireless sensing.

2.1 Mobile Ad-hoc Networks

Mobile ad-hoc networks consist of mobile devices that are interconnected to achieve unicast or multicast communication similar to fixed networks in the absence of infrastructure. Typical application areas named in the literature [6] are communication among rescue workers in disaster areas, message exchange between soldiers during military operations or range extension of access points.

MANET research concentrates on the design of communication protocols that allow to exchange data over multiple hops using unicast, multicast, and flooding. Key research directions for MANETs encompass *routing* for dynamic topologies [28], *medium access* [19] and *congestion control* for multi-hop wireless networks [13], providing *quality of service* despite the characteristics of wireless links and node mobility as well as *preventing selfish behavior* of individual nodes [22].

2.2 Wireless Sensor Networks

A Wireless Sensor Network [2] typically consists of a number of immobile sensor nodes each equipped with a sensing device, micro-controller, radio transceiver and power supply. The task of the network is to perform distributed measurements and to transfer these to one or more sinks for analysis and interpretation.

Research areas in WSN can be divided into three main directions. The first copes with the challenges of *distributed sensing*, for example sensor calibration, time synchronization, and node positioning. The second group consists of solutions for *communication*. As there is no infrastructure available and a sink may not be within direct radio range of each node, the network needs to be capable of self organized multi-hop transmissions [16]. In contrast to MANETs the communication in WSNs is data centric. Thus the information is not transmitted via unicast, multicast or flooding. Instead the information of the individual nodes is typically aggregated as it is passed from node to node on its way to the sink [11]. The third research area in WSNs is dealing with *resource constraints* of the used nodes. Especially energy awareness is of concern here. This led to research on power aware routing [8], sleep cycles [34] and in-network computation/aggregation techniques [18] reducing the amount of transmitted data. Furthermore, as the network should also work when some nodes fail, e.g. due to depleted batteries, fault tolerance [12] has gained increasing interest.

2.3 Infrastructure-based wireless networks

Infrastructure-based networks provide a mobile user with different network services by means of a fixed infrastructure. In such networks, only the last hop is wireless, the user communicates directly with the nearest station. Examples are mobile phone systems (GSM [9], UMTS [31], IMT-2000 [15]) or the well known 802.11 WLAN [14]

Infrastructure-based networks are more mature than the previously described networking technologies. They are already in productive use, offering popular services like *telephony*, *text messaging* or *data transmission*. These networks typically support unicast, but some are also able to provide multicast and broadcast communication.

3 Applications of inter-vehicle communication

In the following we outline classes of car-to-car communication applications frequently described in the literature (see, e.g. [20, 7, 3]). We then discuss the applicability of MANET, WSN or infrastructure-based communication as a way to implement these applications.

3.1 Safety Applications and Cooperative Driving Systems

Safety Applications transmit information about unforeseeable and potentially dangerous events. One example is an emergency braking warning transmitted to all the cars following the braking car. Cooperative Driving Systems are designed to automatically influence the behavior of a group of cars. These include speed management to avoid traffic jams, automated highway entering or coordination of arrival times at an intersection.

Applications from both classes require the fast delivery of information to the cars in the affected area, typically in the originator's neighborhood. Interest in a message is defined by the physical location rather than a node's identity, thus the identities of the receivers are unknown to the sender.

This communication pattern with unknown receiver identities does not match the unicast or multicast communication patterns supported by infrastructure-based technologies. Furthermore, relaying a broadcast via an infrastructure network consumes precious time.

Similarly the communication pattern does not match that of wireless sensor networks: the data needs to be distributed among all vehicles in a certain region rather than to one or more dedicated sinks.

A frequent assumption is that MANET flooding and geocasting algorithms can be used to implement the required functionality. But the events of interest for safety or cooperative driving applications can be sensed by a number of cars at the same instant. When all these cars transmit this information by means of flooding or geocasting, this can easily overload the network. Therefore, identifying application-level *events* and their aggregation and filtering is of importance which renders current MANET approaches unsuitable for this type of applications.

3.2 Driver Information Systems

Driver Information Systems provide the driver with additional information about the current conditions that lie ahead with the aim to increase the range and quality of awareness. This could be information on weather, road conditions or traffic jams [32] as well as electronic road signs or parking places [4].

These systems need to transmit information about a certain area that can have a substantial size (e.g., covering a city) to a large number of users, possibly to all the users in that area. The transmission is neither time critical nor is it necessary to supply a fully-detailed description. Thus intelligently filtered or compressed information suffices in most cases as the desired level of detail decreases with distance and time.

The main building blocks of a driver information system are *information collection* and *information distribution*. Although the primary purpose of wireless sensor networks is collecting information, they are usually designed to transmit this information to one static sink, not to a large number of mobile nodes.

Infrastructure-based networks on the other hand are well suited for information distribution, but lack solutions for information acquisition. Therefore the infrastructure would have to be extended with some sort of sensing devices. While this might be feasible for traffic hotspots, it seems quite unlikely that the whole network of roads will be covered in this way.

Since the required communication type is based on data acquisition and aggregation, MANET technology is not appropriate for this application class. Neither unicast nor multicast nor flooding are usable for disseminating such data.

3.3 Internet Access

Internet access is a frequently cited application for vehicular networks [17, 25]. It comprises all applications that require a connection to a fixed server such as web browsing or email. Due to this connection at least one gateway between the wireless and the fixed network is required. Capacity limitations in wireless multi-hop networks [10] as well as latency bounds in fact enforce a large number of gateways. This leads to an infrastructure-based solution. Even if it were technically possible, there are no economical reasons to duplicate the functionality of existing (and already deployed) solutions like UMTS by means of MANETs or WSNs.

3.4 Point-to-Point Communication within the network

One can also think of applications like chatting or file exchange that require a connection between specific cars within the wireless network.

Clearly such communication reaches far beyond the WSN paradigm where unicast within the sensor network is not supported. In wireless multi-hop networks like MANETs, only short range connectivity is feasible due to the above mentioned capacity limitations. Such short range connectivity results not in unicast but in fact in some form of directed flooding: cars mainly drive along the roads, thus a message transmitted over a few hops between the vehicles will be received by all cars in the neighborhood. Furthermore, short as well as long distance, high performance point-to-point connections can already be realized via existing cellular phone systems. Thus infrastructure-based networks seem to be the best suited technology for most of these applications.

4 Additional System Design Factors

In this section we examine additional factors that influence the design of an inter-vehicle communication system. While some of these are also relevant for existing network types, others are unique for vehicular communication.

Network evolution is one of the key issues in these vehicular communication systems. Upon introduction of car-to-car communication in the consumer market, only few equipped cars will be present. This number will increase over time but it may take very long until all vehicles are equipped. Furthermore, due to the long lifetime of cars, first generation technology will be around for a while[1]. The slowly increasing penetration rate as well as the presence of legacy devices yields a number of challenges: 1) As consumers only buy technology useful for them, IVC needs to offer working services right from the start, i.e. already with only few equipped cars. 2) Nevertheless, these services need to keep working with an increasing number of equipped cars. 3) Future and legacy applications need to work in parallel, thus they need to be designed for coexistence with respect to both hard- and software (e.g. by intelligent and adaptive bandwidth usage). 4) Hard- and software update strategies need to be developed, with a special focus on security and safety issues.

Variable node density is—besides being interwoven with network evolution—also influenced by random node distribution. Even at 100% equipment rate it is likely that only few cars are available in a certain area, on the other hand it is possible that a substantial number of such cars concentrate in a small area already at a low fraction of equipped vehicles. For that reason inter-vehicle communication as well as the applications built on this paradigm must be flexible in terms of node densities.

Dealing with *global device mobility* is another important factor. As it is difficult to limit the movement of users to a certain area[2], the delivery of the first IVC-equipped car leads to the potential presence of the technology everywhere in the world. This extends the problem of compatibility and imposes some interesting demands on applications, e.g. with respect to country specific peculiarities like left hand versus right hand traffic.

Safety, Security and Privacy are crucial, self-contradictory issues to consider while thinking about inter-vehicle communication. When designing an IVC system, safety should have the highest priority as any malfunction of the system endangers human life. Besides that, the presence of a wireless communication device integrated in the car increases the probability of system manipulation from the outside. Thus high security standards are necessary. Furthermore, confidential, private data like car position should be handled with appropriate care not to violate the need of personal privacy.

Although computing power, memory and energy are a cost factor in car production and thus not available unlimitedly, they are not as constrained as in WSNs and

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[1] Just consider the number of veteran cars that are still present on todays roads.

[2] It will obviously reduce the technology's acceptance if users are not allowed to drive to certain countries due to regulatory issues.

MANETs. In the context of the available information, *information richness* is dominating in car-to-car communication systems as a lot of sensors are already integrated in modern cars. The information of these sensors is needed by other systems of the car and thus comes for free. Constraints like device size are only of marginal importance as well. The only resource with strong limits is the available bandwidth. It has to be used economically to provide enough space for future applications.

5 Research Directions for Inter-Vehicle Communication

As we have shown, the envisioned applications require communication patterns that cannot be provided by mobile ad-hoc networks and wireless sensor networks. Moreover there exist some additional design factors that need to be taken into account when developing inter-vehicle communication systems. In order to find ways to meet these unique demands, we decompose the communication patterns and additional conditions into a number of (sometimes overlapping) problems that need to be solved. These problems in fact result in a list of potential *research directions*. This section sometimes uses well-known terms like “aggregation” used in the database or sensor network context to name these directions. This shows that related problems also occur elsewhere but the solutions cannot be directly applied.

We believe that a future inter-vehicle communication network will be composed of a number of vehicles equipped with sensors and a radio transceiver. The cars exchange information such as sensor readings with their direct neighbors. Vehicles cooperate, i.e. they forward and process the messages to establish a decentralized system, reaching far beyond the limits of connectivity between individual peers. This system will neither use nor provide long range point-to-point connections.

Safety applications and cooperative driving systems require a secure, fast distribution of information about an event possibly sensed by multiple cars to all vehicles in a limited area. An important building block for this communication pattern is *event differentiation* as the affected cars may provide individual views of the same event. Based on this, it is then necessary to *filter and aggregate* the information about the event in order to reduce the amount of transmitted data and decrease latency. The information about an event needs to reach all interested cars. Thus it is necessary to identify interested cars and to *forward the information*, if possible with guaranteed reliability and limited delay. For further reading and a first approach how to cope with these requirements, refer to [30].

Driver information systems provide each user with information on the road conditions in a large region. As it is neither possible nor necessary to supply detailed description to all users in the area, an interesting problem is the *compression and aggregation* of the information. Some solutions for that can be found in [24,32,4], they are however strongly application dependent. Users will probably have a large interest in information about the area directly in front of the car and less interest in areas that are farther away or behind them. Determining the detailed parameters of this interest results in an *interest profile* that can be used as basis for compression and aggregation. It is also necessary to develop techniques for data transmission that can take advantage of the *delay* *tolerance* of the applications, e.g. by letting messages travel on-board of other cars as suggested in [33].

Feasible point-to-point connections within an inter-vehicle communication network will be of short range and duration. So far no applications for these type of connections have been proposed. Therefore developing applications that exploit such temporary channels can be a tempting research direction. As the examples of the world wide web or the text messages in mobile phone systems show, the network designers are often not the ones that develop the killer applications or decide on their success. Thus *providing an open API* that allows the development of such applications should be considered. The work of [23] is an example of research towards such an API but it is not yet a final solution.

Another interesting research area is the *integration* of existing or envisioned car-to-infrastructure communication systems like road fee tolling or car diagnosis. Although these applications do not fall within the scope of car-to-car communication, they can use the same hardware. This reduces the number of wireless communication devices installed in the car, thus lowering cost and improving market introduction. The prerequisite is the compatibility with the IVC system itself as well as with existing systems. As such applications will often exchange private data, the wireless channels must implement high security and authentication standards.

Due to the long lifetime of cars, one of the biggest challenges regarding the network evolution is backward as well as forward *compatibility*. This must be considered already during the design of hard- and software. The penetration rate is another crucial factor here, posing the initial question: which application is feasible at which network development phase. It is especially necessary to develop attractive applications for low penetration rates as this will stimulate users to invest in the new technology and speed up the increase of penetration rate. One can also call this the development of *market introduction strategies*, see [21] for more details. These first applications can exploit the fact that initially, a lot of bandwidth is available. However, as new and old applications should coexist, network and application designers should use it carefully: *economical usage of bandwidth* is advised. The authors of [27] acknowledged the problem of limited bandwidth and proposed a solution.

Variable node density requires methods to *discover the current state of the network* as some applications only work properly when the node density is high enough. Furthermore, it is questionable if 100 % equipment rate can be ever achieved as already a damaged radio device can hinder a car to participate. Therefore, special care must be taken for applications that rely on such an equipment rate.

Global device mobility imposes high demands on the flexibility of applications. They need to be *aware of differences*, global ones that exist between countries as well as local ones between city and highway environments. This device mobility also results in *slow upgrade speeds* when new system software or applications need to be introduced. This makes it difficult to determine the time at which a new application can be considered as “deployed”. The designers have to use *smooth introduction* of new applications rather than expect the possibility of massive updates. Such an approach will result in a high heterogeneity in the application environment. Furthermore, with increasing density of equipped cars, one single, *global vehicular network* will emerge (in terms of possible car deployment, not in terms of global connectivity). The consequences of this need to be examined.

Introduction of electronic systems that can influence the driving behavior of a car based on information flowing from the outside world is a real breakthrough, but it also opens the up to now closed world of car IT to malicious attacks. Especially techniques for *message authentication* and *node's identity revocation* are necessary. On the other hand exchanging private data like car position and speed in driver information systems raises the question of *privacy protection*. A balance between system functionality and users' privacy has to be found. There is an obvious conflict between authentication of the message and privacy needs. [29, 26, 1] present some proposals on how to cope with this challenge, however no optimal solution has been found yet.

A lot of sensor information is already available in todays cars, and the number of sensors will continue to grow. Therefore, there is a need for an *Open Message Format* that allows to smoothly integrate readings of existing as well as new sensors. Such messages should also be able to carry data of future applications, thus the message format must be extensible. This also allows cars that are themselves not equipped with this type of sensors to recognize and process new information. In [5], such an open package format is described for MANETs in general and [27] contains a first proposition how to deal with this issue in the context of IVC.

In contrast to bandwidth, battery and computing power as well as memory are not expensive. It is even possible that future cars will have a lot of free capacity. Furthermore, the above mentioned sensor information is available at no additional cost. Thus, there exists the possibility to save bandwidth by means of strong *in-network computation* and by exploiting additional information.

6 Conclusions

We have shown that the applications envisioned for inter-vehicle communication require functionality differing fundamentally from the services offered by mobile ad-hoc networks. Thus inter-vehicle communication is not the (quite desperately needed) application area for ad-hoc network technology. However, it does pose numerous unique and novel challenges from network evolution to event detection and dissemination, making research in this area very attractive.

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