Report from Dagstuhl Seminar 13392

Inter-Vehicular Communication – Quo Vadis

Edited by

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Abstract

"Inter-Vehicular Communication – Quo Vadis?". With this question in mind, leading experts in the field of vehicular networking met in Dagstuhl to discuss the current state of the art and, most importantly, the open challenges in R&D from both an scientific and an industry point of view. After more than a decade of research on vehicular networks, the experts very seriously asked the question whether all of the initial research issues had been solved so far. It turned out that the perspective changed in the last few years, mainly thanks to the ongoing field operational tests in Europe and the U.S. The results point to new research directions and new challenges that need to be solved for a second generation of vehicular networking applications and protocols. In four working groups, the experts studied these new challenges and derived recommendations that are also very helpful for the respective funding organizations.

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1 Executive Summary

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Motivation

The management and control of network connections among vehicles and between vehicles and an existing network infrastructure is currently one of the most challenging research fields in the networking domain. Using the terms Vehicular Ad-hoc Networks (VANETs), Inter-Vehicle Communication (IVC), Car-2-X (C2X), or Vehicle-2-X (V2X), many applications – as interesting as challenging – have been envisioned and (at least) partially realized. In this context, a very active research fields has developed.

There is a long list of desirable applications that can be grouped into four categories:

- eSafety applications that try to make driving safer, e.g., road hazard warning;
- traffic efficiency applications aiming at more efficient and thus greener traffic, e.g., detection of traffic jams;
- manufacturer oriented applications, e.g., automatic software updates; and
- comfort and entertainment applications, e.g., automatic map updates or video streaming.

While there are some similarities with fields like mobile ad-hoc networks or wireless sensor networks, the specific characteristics of vehicular networks require different communication paradigms, different approaches to security and privacy, or different wireless communication systems. For example, the nodes usually do not have severe power and form factor constraints, and they might be always on. On the other hand, due to high relative speeds, wireless connections may not be stable for a longer time period and the network density is expected to vary from sparse to very dense networks. Another challenging issue is the efficient use of available infrastructure, such as road side units or even cellular networks. Furthermore, IVC has strong links to other research domains, e.g., geo-informatics as it requires very precise localization and precise maps or highly scalable simulations that are a requirement for analyzing traffic systems with hundreds or thousands of vehicles.

In the past, many specific solutions for IVC have been identified and now, industry and other stake-holders are already calling for standardization. Still, we believe that many important research questions have only been partially answered and the approaches discussed in the standardization bodies are based only on a minimum consensus of simplest solutions. Security and privacy, scalability, use of advanced communication patterns like aggregation, transmit power control, and optimal medium access are just a few of such issues.

In 2010, a first Dagstuhl Seminar (10402) was organized on the topic of inter-vehicular communication [1, 2]. The motivation was to bring together experts in this field to investigate the state of the art and to highlight where sufficient solutions already existed. The main outcome of this very inspiring seminar was that there are indeed areas within this research where scientific findings are being consolidated and adapted by industry. This was the consensus of quite intriguing discussions among participants from both industry and academia. Yet, even more aspects have been identified where substantial research is still needed. These challenges have been summarized in the Dagstuhl report [1] and in an IEEE Communications Magazine article [2].

Objectives

It was the goal of this new seminar to again bring together leading researchers both from academia and industry to discuss if and where the previously identified challenges have been adequately addressed, and to highlight where sufficient solutions exist today, where better alternatives need to be found, and also to give directions where to look for such alternatives. Furthermore, the goal of this workshop was to go on step beyond and identify where IVC can contribute to the basic foundations of computer science or where previously unconsidered foundations can contribute to IVC.

The 2010 Dagstuhl seminar promoted a “top-down” approach to inter-vehicle communications instead of the classical “bottom-up” approach. With the top-down approach, the effects of applications are first analyzed under the assumption that the communication system will be able to support the application. Thus, an “upper bound” can be presented on the benefits of IVC. In our discussions, we summarized all the scientific work that followed this approach after the previous Dagstuhl seminar and contrasted it with new insights based on field operational tests, safety application design and massively distributed operations.

In particular, we shifted the focus from basic networking principles to applicability in real world scenarios. In the last few years, first field operational tests have been conducted in the US (the Michigan field trial) as well as in Europe (SIM-TD in Germany, DRIVE C2X in Europe). Lessons learned from those tests applied to currently used models and concepts will bring new insights into the forthcoming research challenges. Among others, questions to be studied include the following still unanswered research challenges:

- Data analysis of current field operational tests: are they validating or invalidating current models?
- Safety applications: show stopper or driving force? What are the limitations in terms of latency and reliability of available communication principles for enabling critical safety support;
- From highly distributed to massively distributed operation: can vehicular networking based on DSRC/WAVE also support all the pedestrians and bicyclists?

We organized the 2013 seminar again as a discussion forum. Three invited keynote presentations were organized to stimulate discussions among the participants. In order to steer the discussions, we prepared four working groups that helps focusing on selected open research challenges. In addition, we also supported ad-hoc presentations on topics of the working groups. The following working groups have been formed and led to very interesting observations:

- Foundations – In this group, it was discussed, which fundamental insights gained in the vehicular networking research domain can be transfered to other domains of computer science. The other way around has been discussed as well, i.e., which areas of computer science might help fostering work in the vehicular networking and which may help overcoming open challenges.
- Field Operational Tests (FOTs) – This group focused on the results that already have been derived from the ongoing work in various test sites in the U.S. and in Europe. The main questions in the discussion were whether the current experiments are already sufficient to gain insights into larger scale behavior or if additional tests are needed.
- IVC Applications – In this group, the applications' perspective to IVC was discussed. In the last years, many of the developments have been done looking at lower layer networking problems. This resulted in a number of networking solutions that nicely support specific applications but cannot be integrated to a generalized networking architecture.
- Heterogeneous Networks – Possibly one of the most important and timely working groups focused on the integration of different networking technologies. This is strongly needed to develop integrated IVC solutions and also to overcome early deployment problems like the initially low penetration ratio.

Eventually, all these questions lead to the big question whether vehicular networking can now be shown to improve efficiency and safety on our streets. We are now in an era that completely changes the game in car manufacturing and road traffic management. Computer science is becoming the key element in the design of these systems. It is of utmost importance to bring in expertise from classical computer science (computer networking, simulation and modeling, operating system design) as well as from electrical engineering (digital signal processing, communication networks) as well as experts from the automotive industry and from the intelligent transportation community.

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3 Overview of Talks

3.1 Studying safety applications for vehicular communications

Natalya An (KIT – Karlsruhe Institute of Technology, DE)

Joint work of An, Natalya; Hartensten, Hannes; Neudecker, Till

In this presentation we point out three current challenges in studying of safety applications. First, there is a need for common and clear definition of an application as a protocol. Second, application requirements need to be justified from a traffic safety perspective. The requirements analysis has to consider kinematics and the driver as well as minimization of false alarms. Such analysis can also be independent of communication technology and simply focus on information that is required. As the last point, we discuss the verification of safety applications on one example application. If safety application can be verified to be fail-safe, how efficient are they? We also quantify the tradeoff between safety and efficiency.

3.2 Fundamental limitations of the basic IVC system and related research questions

Andreas Festag (TU Dresden, DE)

The talk gave a brief overview of the IVC system that has been standardized in Europe and tested in FOTs, such as simTD, DRIVE C2X, etc. This system is also referred to as "basic system for initial deployment". From this reference system key limitations of the system covering physical transmission, medium access, networking, messaging, and congestion control; these limitations are linked to research challenges for future IVC taking that takes into account the (hopefully) coming deployment.

3.3 Play The Game

Raphaël Frank (University of Luxembourg, LU)

We are moving towards a cooperative world. Most people nowadays have ubiquitous Internet connectivity through their mobile devices. Social Networks have now become a part of our daily lives. They allow us to discuss and interact with virtually everybody on the plant. This platform enables a plethora of new cooperative applications including "social games". The idea here is to increase the efficiency of a system by building a game around it. In the context of vehicles, one could think of various gaming scenarios to increase road safety, decrease consumption or reduce traffic congestion by providing a score and rank to the participants.

3.4 Quod Vides? The Eyes of the Vehicle Computing Cloud

Mario Gerla (University of California – Los Angeles, US)

New vehicle applications have recently emerged in several areas ranging from navigation safety to location aware content distribution, intelligent transport, commerce and games. This diversity of applications sets the Vehicular ad Hoc Network (VANET) apart from conventional military and civilian emergency MANETs and does introduce new design challenges. In this talk we review the recently defined VANET standards, introduce emerging vehicular applications and examine the new services they can provide. A representative service scenario is urban sensing: vehicles monitor the environment, classify the events, e.g., license plates, chemical readings, radiation levels, and then generate metadata of what they observed. The metadata in turn can be uploaded to Internet servers or can be kept on board of vehicles to support future services such as forensic harvesting by Authorities. The notion of VANET Services suggests that the VANET can be viewed as a mobile service providing Cloud. In fact the VANET is an important example of a new type of Cloud, the Mobile Computing Cloud (MCC). The MCC consisting of mobile agents (people, vehicles, robots) that interact and collaborate to sense the environment, process the data, propagate the results and more generally share resources in order to produce mobile services that are not efficiently supported by the Internet Cloud. In this talk we will revisit VANET applications and services in light of this Mobile Cloud model. We will also address the cooperation between Vehicular Clouds and the Internet Cloud in the context of a vehicular traffic management application.

3.5 Do Vehicular Networks Scale? Early Lessons from Field Trials and Simulations for Academic Research

Marco Gruteser (Rutgers University – New Brunswick, US)

After the past decade of vehicular network protocol research and standardization, vehicular networks have now moved into a field trial stage. The Scalability Field Trials, which are planned and conducted by the CAMP VSC3 Consortium in cooperation with the USDOT, are trials that seek to identify a transmission control protocol for scalable V2V safety communications. Such a protocol should preserve the performance of V2V applications in both congested and uncontested communication environments. To this end, 200 DSRC equipped vehicles were driven in dense configurations on testing grounds with key network performance indicators logged. We now use the experimental data to calibrate and validate ns-3-based simulation models, which can then be used to predict performance in even denser configurations. After implementing appropriate capture and propagation models as well as correcting MAC inaccuracies our initial simulation results show good agreement with the field tests and promising results on transmission control algorithm effectiveness.

3.6 IVC – Beyond DSRC & Beyond Vehicles

Jerôme Haerri (EURECOM – Biot, FR)

IVC has been associated to DSRC for dedicated wireless communications between vehicles. In a larger context of smart cities, IVC may be extended beyond DSRC and beyond vehicles. In this talk, we investigate the feasibility of device-to-device LTE communication (LTE-Direct) in a traffic safety context. We extend LTE-Direct for periodic broadcast transmission of beacon messages containing mobility states (aka CAM in EU, BSM in US). We propose to employ a quasi-static OFDMA downlink resource allocation similar to eMBMS, where multiple eNBs reserve LTE downlink resource blocks for dedicated device-to-device communication. Considering an optimal resource allocation between all vehicles covered by the eNBs, our proposal may sustain up to 100 vehicles transmitting beacons at a rate of 10Hz. Although challenges remain to efficiently allocate the reserved OFDMA resources in a fully distributed way, our proposal is a first attempt to show that the LTE-Direct technology may be used for traffic safety applications in a larger context of mobile (pedestrian, bicycles, cars) rather than only vehicular communication.

3.7 Exploring Space – towards high-capacity inter-vehicular communications

Geert Heijenk (University of Twente, NL)

This presentation discusses the question 'Are there still research challenges in inter-vehicular communications'. The premise is that these may come from autonomous, or rather coordinated driving. I will start with a few results from an earlier project, Connect & Drive, where a system for cooperative adaptive cruise control was researched, designed, and prototyped. We project that for coordinated driving, important challenges are in the area of reliable consensus for coordinated manoeuvres, and high-rate beaconing for increased situational awareness of vehicles. I show that current systems do not suffice for these challenges. In order to increase the scalability of inter-vehicular communications, I propose to explore spatial reuse, by using cheap large-scale antenna arrays and beamforming receivers. This way, a vehicle can be equipped with a large number of receivers, each receiving from a specific (dynamically reconfigurable) direction. Given this idea, I point at important research questions, and argue that for a good understanding, the use of good analytical performance models is of paramount importance.

3.8 Are Generic Communication Systems Possible?

Frank Kargl (Universität Ulm, DE)

In this talk we raise the question how IVC communication systems can be made more flexible and future-proof. As we introduce a first generation of IVC communication systems, we also need to be prepared for an evolution that includes introduction of additional new applications, aggregation protocols, or other elements. We propose a lightweight framework were nodes in the network can introduce at deployment time new components that can alter or extend the behavior of the system. For example, an application that requires a new algorithm for aggregation data in the network could provide such a component when it is deployed in the network.

3.9 Do We Need … in IVC?

Renato Lo Cigno (University of Trento – DISI, IT)

In this short talk I briefly point out and stimulate discussion on some of the "golden fleece" that are being pursued in the ICV area for safety applications and that are probably slowing down research and jeopardize adoption. There is a hype that safety application require a networking support similar to a deep space mission, where a single failures means losing a billion dollar project. Safety in traffic, instead, means improving the current situation, dominated by human errors and where, worldwide, an estimated trillion (1012) USD are spent because of car accidents, not counting for casualties maimed people and social costs in general. Thus, I argue that the fundamental scientific questions that should be addressed by this community relate to the minimal amount of information needed for vehicles to react, and not to deliver all information, relate to devising randomized, distributed protocols and algorithms that improve the situation and integrate with sensors on board, rather than finding the one-system-fit-them-all perfect solution.

3.10 V-NDN: Vehicular Named Data Networks

Giovanni Pau (University of California – Los Angeles, US)

In this work we apply the Named Data Networking, a newly proposed Internet architecture, to networking vehicles on the run. Our design, VNDN, illustrates NDN's promising potential to providing a unifying architecture that enables networking among all computing devices independent from whether they are connected through wired infrastructure, ad hoc, or intermittent DTN. We also describe a proof-of-concept V-NDN implementation.

3.11 Platooning and Network Related Challenges: Solutions and First Results

Michele Segata (University of Trento – DISI, IT)

Platooning, the idea of cars autonomously following their leaders to form a road train, has huge potentials to improve traffic flow efficiency, driving experience on freeways, and most importantly road traffic safety. Wireless communication is a fundamental building block for this application – it is needed to manage and to maintain the platoons. However, strict constraints in terms of update frequency and reliability must be met. In this talk, we analyze the performance of information dissemination strategies for platooning based on DSRC/WAVE. In particular, we developed communication strategies exploiting synchronized communication slots as well as transmit power adaptation. We evaluate the performance of the controller under different update frequencies, showing that beacon frequency could be adapted depending on the dynamics of the platoon. Using the platooning simulator we developed, we demonstrate the effectiveness of a combined TDMA plus transmit power control scheme even in dense vehicular scenarios.

3.12 Heterogeneous Vehicular Networking

Christoph Sommer (Universität Innsbruck, AT)

Heterogeneous vehicular networks are not a new concept by far: always best connected transmission of data over one of a set of channels has been shown to be highly beneficial to increase connectivity and combat low equipment rates. We show that heterogeneous vehicular networks can do more than that: by making smart use of the different properties that, e.g., cellular and short range radio channels offer, we can provide new and better services, such as cellular assisted intersection collision avoidance.

3.13 Design of Congestion Control for Vehicle Safety Communications

Tessa Tielert (KIT – Karlsruhe Institute of Technology, DE)

In this talk, we address three questions about congestion control in vehicular safety communications. First, do we need it at all? Second, if we do need it, how should we do it? Typical "turning knobs" are transmit power and message generation rate. In addition, safety communications should provide "fairness" and "awareness". And finally, what is still to do in this field? We start by addressing the spatio-temporal requirements of awareness. We then study the potential of the communication system to minimize packet inter-reception time (IRT) at a certain sender-receiver distance and identify the parameter combinations optimizing this metric. We show that a fixed parameter setting is ineffective, transmit power control and message rate control each leave room for improvement and a joint control strategy seems to provide best results. We discuss different aspects of fairness and introduce the concept of basing fairness not on the share of bandwidth but on the achieved safety benefit. However, a concrete definition of this concept requires a clear understanding (and metrics) of safety applications' requirements, which we see as a major challenge for the future.

3.14 Potential benefits from (DSCR)-C2X – Questions from a traffic engineer

Peter Vortisch (KIT – Karlsruhe Institute of Technology, DE)

After ten years of research and development, intervehicular communication based on DSRC is ready for deployment. What benefit can they produce, from a traffic engineering perspective? Promises were made to improve safety, efficiency, fuel consumption and even travel behavior. Many of the intended applications generate warnings about some dangerous situations. This is a natural domain of DSCR, and given the lower latency compared to cellular communication, a certain benefit can certainly be generated. But for hard safety applications like collision avoidance, cars will still rely on autonomous sensors in the first place. Besides safety applications, traffic efficiency is addressed. One of the prominent application examples is communicating with traffic signals. The cars are informed about green or red times and can adapt their approach to avoid stopping and thus save fuel. The problem here is that there are not many fixed time signals left since traffic control is vehicle actuated in most intersections because of pedestrians or transit priority. And even in the case of fixed time signals, the time frame in which the given information can be useful is pretty short. In general, it is not easy to make a convincing case at the moment for DSRC systems to improve traffic efficiency significantly, partly because many applications are already "taken away" by cellular communication based systems. In interesting field for future research will be the interaction of vehicular communication and the rise of automated driving.

4 Working Groups

4.1 Heterogeneous Vehicular Networks

Claudio Casetti, Falko Dressler, Mario Gerla, Javier Gozalvez, Jerôme Haerri, Giovanni Pau, and Christoph Sommer

4.1.1 Introduction

A future trend of vehicular networks is the move away from focusing on just a single technology and towards designing systems that can make use of multiple different technologies, creating *heterogeneous vehicular networks*. Looking into the literature, however, the underlying assumptions, concepts, and even the goals of such approaches are very fuzzy. In an effort to move this research area forward by clarifying the foundations, identifying commonalities and differences of existing approaches, and outlining future research directions, a working group was formed at Dagstuhl Seminar 13392 to tackle these questions.

The group meeting kicked off by defining the concept of heterogeneous vehicular networks. In the context of networking in general, the term heterogeneous networking is sometimes used as a catch-all definition: for example, there is a clear consensus within 3GPP to define the integrated large-cell/small-cell coverage in LTE-advanced and its related issues as heterogeneous networks. Such definitions do not apply to our case.

In vehicular networking it was agreed that a *Heterogeneous Vehicular Network* is to refer to a system characterized by the integration of different technologies such as IEEE 802.11[p] DSRC together with higher layer protocols such as WAVE [1] or ITS G5 [2], IEEE 802.11[abgn] consumer WiFi [3], and 3G/4G cellular networks.

4.1.2 Motivation

One of the key motivations for considering such heterogeneous vehicular networks is the widespread availability of multiple technologies – both on today's portable devices like smart phones and in modern cars' sat nav systems or multimedia units.

Further, the team was quick to agree that – while cellular networks, such as LTE, will be a big helper during any initial rollout of short range communication technology – cellular networks will, in the medium term, not be able to offer sufficient network capacity without a drastic increase in deployment density and/or price [4, 5]. They might, in the long term, even be unable to offer sufficient capacity.

Heterogeneous vehicular networking is further motivated by the fact that each of the currently available wireless technologies offers unique benefits, but also unique drawbacks. It was argued that the reasons to have WiFi lie in the downloading of added-value content and in the creation of a truly integrated environment, which would not be limited to cars as the only road users: Indeed, WiFi would foster the integration of bicycles and pedestrians into the network. Further, because of its tailored physical layer, dedicated channel(s), and tight locality, DSRC can offer unique benefits in safety and cooperation awareness applications, due to their tight latency requirements. On the other end of the spectrum, cellular technologies are widely available, and designed for delivering large amounts of data over arbitrary distances. On the down side, they could face further hurdles when multicasting or local broadcasting is a strong requirement. Indeed, the lack of specific multicast support even in current 4G networks, coupled with multi-operator terminals, is a critical limitation [6].

The team identified two basic, opposing trends in heterogeneous vehicular networking that can be classified as follows:

(A) pushes for a generalized network stack that abstracts away from lower layers to decouple applications from the employed technology, aiming to provide *data offloading* services, or an *always best connected* experience to upper layers.

(B) follows a *best of both worlds* approach, exposing information and control of lower layers to applications, enabling them to selectively use the best fitting technology for a particular task.

4.1.3 Class A

Having multiple technologies at hand gives vehicles the option to communicate in an always best connected fashion. This allows them to efficiently combat hard to predict local shadowing and fading effects. Further, it allows them to operate even in very sparse networks, unhindered by network fragmentation or similar problems that would plague a purely DSRC based solutions early after market rollout.

Further, using multiple technologies in parallel for sending can make the delivery of 'one in a million' safety messages much more robust. It can further help thwart physical layer attacks or serve to cross-validate potentially fraudulent messages.

The discussion then moved to the use of DSRC for cellular offloading to increase capacity. The consensus was that many literature works already explored cellular offloading [7], but that the main applications seem to involve some variations of the caching-and-forwarding concept. However, in order to be effective, caching must be applied to popular content. It was remarked that there are no reliable studies of how "popular" content must be so as to turn offloading into a viable option.

In a similar vein, it is possible to use one technology to deliver a basic level of service, and another for optional, enhanced levels of service, e.g., the base layer and enhanced layers of scalable video coding [8].

4.1.4 Class B

As an alternative to the more straightforward *always best connected* abstract approach discussed previously, heterogeneous networks could also much more directly instrument multiple technologies, employing each to its full capacity and according to its particular benefits and drawbacks.

We categorized approaches in this class into two sub-classes:

(B1) chooses the underlying technology according to a *control/data* split.
Sending control information via a cellular channel, if available, can ensure that control information reaches the highest number of nodes, independent of network topology, and even kilometers in advance. Sending data via multihop DSRC can serve to ensure that the network load caused by such data exchange remains local only.
One example of such a network is the MobTorrent approach [9], which employs a cellular network for transmitting control data to WiFi access points, allowing them to prefetch and cache data to offer Internet access to vehicles.
A more recent example turns this architecture on its head, utilizing DSRC for service announcements and a cellular network for supporting infotainment data dissemination [10].

(B2) splits data according to a *local/global* decision.
Local collaboration via DSRC if necessary (and, thus, if available) can make best use of the low latency offered by this technology. Medium-scale or global collaboration via cellular networks, transmitting only aggregate information, can supplement local collaboration: it can exploit the universal availability of cellular networks without causing undue load and without suffering from its drawbacks for local communication.
One example of such a network is a clustering approach [11], which employs short range radio for near field information exchange in clusters and cellular networks for interconnecting clusters.

4.1.5 Conclusion

The group meeting adjourned after identifying three promising research directions for heterogeneous vehicular networks:

- combining technologies with long-range and short-range coverage: they have different objectives but a positive fallout is expected from their joint deployment;

- investigation of the feasibility of integrating a high number of different radio technologies into one device; investigation of Software-Defined Radio (SDR) as a potential way forward [12];
- further investigation of offloading, scheduled downloading and relaying is needed, identifying promising use cases;
- continuing development of safety protocols and applications, under the premise that, though safety may not carry much money it is the only option to make DSRC mandatory on newly-manufactured vehicles.

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4.2 Fundamentals: IVC and Computer Science

Javier Gozalvez, Jerôme Haerri, Hannes Hartenstein, Geert Heijenk, Frank Kargl, Jonathan Petit, Björn Scheuermann, and Tessa Tieler

The working group on "Fundamentals: IVC and Computer Science" discussed the lasting value of achieved research results as well as potential future directions in the field of inter-vehicular communication. Two major themes 'with variations' were the dependence on a specific technology (particularly the focus on IEEE 802.11p in the last decade) and the struggling with bringing self-organizing networks to deployment/market.

The team started with a retrospective view and identified the following topics as major contributions in the last decade: analysis and design of single-hop broadcast communication and geonetworking, scalability issues (for both, small and large penetration rates) as well as corresponding security and privacy approaches. In addition, all the work also led to a strong requirements elicitation for the domains of safety and efficiency applications bringing together traffic experts, automotive engineers and the IVC community. The working group considered various contributions to have a lasting value, particularly analytical models for information dissemination, approaches to control or to avoid congestion of the radio channel, building control applications on top of the unreliable wireless communication as well as a bunch of security approaches like broadcast authentication and misbehavior detection. In addition, the working group tried to check whether results from the previous Dagstuhl seminar on Inter-Vehicular Communication in October 2010 has led to new research directions and results. In the 2010 seminar, the participants proposed to put more focus on the applications and the assessment of their benefits, first ignoring too many technical details and then adding technological constraints successively. Several research results appeared to have followed the proposed roadmap, see for example [1, 2, 3].

The working group then did a 'gap analysis', touching the following two issues: a) to what extend should IVC research 'tailor' a specific technology and b) should the interaction with other research communities be strengthened? The working group identified fault tolerance, reliable consensus and cognition as computer science fields that should be more involved in IVC research. In addition, the engineering and deployment issues appear to deserve more attention, thus, an easy answer on how much 'tailoring' and how much 'general results' are needed could not be given.

As a result of the discussions, the following research topics showed great promise to the working group members:

- Group communication, application protocols and reliable consensus. While in the last decade the focus was on one-hop broadcast messages, with coordinated maneuvering and automated driving a group of vehicles needs to communicate reliably, with a specified application protocol, to achieve reliable consensus. As vehicular traffic is full of protocols, it is no big wonder that maneuvering requires application protocols. However, group formation and dealing with the unreliable wireless channel brings interesting research questions in.
- Cognition and safety. The cooperation with experts from cognitive vehicles and from automotive safety should be strengthened since application requirements come from detecting dangerous traffic situations (including pedestrians and bicyclists) as well as of safe driving strategies.

- Self-organizing systems. The promise made by the IVC community to design self-organizing networks is not enough for deployment or market entry, as many field operational tests clearly show: the radical new design of the network alone and the sheer scale of the system requires many innovations in the whole IT management chain. Here again, principles from self-organizing systems and the whole self-x movement might help while being complemented by existing IT management techniques.
- Flexible and adaptable communication architectures that can adjust to changing contexts, technologies and application mixes and that allows the system to evolve over time. This would also open a chance for building networks that go beyond IVC and would lead towards an Internet-of-Things approach.

With future cooperative automated vehicles, all the aspects mentioned above require and deserve further efforts in the field of inter-vehicular communication.

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4.3 Best Practices for Field Operational Testing

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4.3.1 Introduction

The performance evaluation of vehicular network technology and applications is a non-trivial challenge. Field testing a system plays an important role in such evaluations and in advancing scientific knowledge. It is not only necessary to assess network performance in a real environment but also to discover previously unaccounted or unknown system properties. While some of these benefits can also be achieved with small-scale experimentation, only Field Operational Tests (FOTs) can evaluate systems at scale and cover a much wider range of scenarios.

Data collected in these trials can furthermore be used as input for the creation and validation of both analytical and simulation models, and therefore improve their quality and relevance. At the same time, conducting meaningful field operational tests is challenging. They often involve complex systems with proprietary technology components, which can make it difficult to interpret the results and to match them to analytical or simulation models.

As vehicular network research and development has moved into a stage of extensive field trials, this working group has discussed the potential impact on academic research and ways to improve collaboration between academia and the operators of field operational tests. We begin with a short overview of ongoing efforts and discuss why field testing can be a necessary and valuable asset for academia and the scientific field. From those discussions we distill recommendations for both academia and trial operators to further improve the value and benefit of future field trials.

4.3.2 Past and Current Efforts

Ongoing field trials in vehicular networks span evaluation topics ranging from driver acceptance of applications to network performance in highly congested environments.

In the United States, the Safety Pilot Model Deployment at the University of Michigan Ann Arbor hosts about 3,000 vehicles equipped with DSRC devices to test the effectiveness of the technology in real world conditions, to measure how drivers adapt to the technology, and to identify potential safety benefits. Results from this test are expected to influence a potential National Highway Traffic Safety Administration (NHTSA) rule making, which could make DSRC technology mandatory.

In addition to this more application oriented testing, the Crash Avoidance Metrics Partnership (CAMP) Vehicle Safety Communications 3 (VSC3) Consortium is conducting field trials under the connected vehicle technology research program of the USDOT. This activity studies scalability aspects of vehicle safety communications that will preserve the performance of vehicle safety applications in both congested as well as uncongested communication environments [1].

In Europe, the German simTD project [2] studied vehicle-to-vehicle and vehicle-to-infrastructure communication based on ad hoc and cellular networks. The trial addressed traffic efficiency applications (traffic monitoring, traffic information and navigation, traffic management) and safety applications (local danger alert, driving assistance) and included vehicles, road side units as well as traffic management centers. The tests were conducted with fleets of vehicles with professional, instructed drivers for scenario testing in a controlled environment and with free-flowing vehicles. The simTD project coincides with trials in other countries across Europe, for which the European project DRIVE C2X [3] enabled a common test methodology and technological basis. Objectives of the tests are to validate the vehicle communication technology and to collect data for impact assessment of the technology on safety and traffic efficiency.

4.3.3 Benefits and Challenges of Using FOT Data

The benefits that the academic community could gain from FOTs are manifold. Research groups studying Inter-Vehicle Communication (IVC) and Intelligent Transportation Systems (ITS) technologies in general, could use the data

ollected during FOTs even after the end of the project, investigating aspects that were not covered by the original FOT objectives. An important requirement for this to be possible is that all needed meta data is logged and documented.

Simulative evaluation of communication strategies and applications in vehicular networks heavily relies on data collected in field trials to further bridge the gap between simulation and reality and hence to increase the trustworthiness of simulation results. For example, the amount of work recently published on channel models for vehicular networks (including path-loss analysis, shadowing models for buildings and vehicles) requires real world data to be validated. The more data is available the better can these models be adjusted and therefore improved. But also MAC layer models would benefit from more extensive experimental validation. The results of network oriented FOTs (e.g., CAMP VSC3) but also more general ones (e.g, DRIVE C2X [3], simTD [2]) can therefore be extremely helpful to validate such models.

Not only can network models be improved with help of field trials but also can they help advance mobility related research. Vehicle traces collected during field tests, for example, could be used to derive behavioral models, which are becoming extremely important for the evaluation of safety applications. Further possible benefits include the tuning of psychological driver models (e.g., the following of recommendations made by the on-board unit) , the parameterization of car following models, or establishing a default mobility scenario to make simulations more comparable towards each other.

However, data access requested by institutions not directly involved in the FOTs requires some preconditions. First, there is a necessity for an in-depth documentation of the published dataset with not only the present goals of the FOT in mind, but also considering that the data will be used for other purposes. This requires a detailed and exact description of the experiments and the data format. Of course, making data publicly available requires specific solutions for data storage policies and locations, as data must be available to download to a potentially wide number of academic research groups, even after the FOT has long been completed.

4.3.4 Recommendations

Although the research community has a long history of analytical evaluations and simulations, the prior experience from FOTs is still rather limited. Since analytical results are used to validate simulators, and vice versa, the gain from having a third tool for performance evaluation is obvious. Some models of real world phenomena already exist in academic research and are used both in simulations as well as analytical evaluations. Examples include wireless channel models, modeling of shadowing and propagation based on different types of road environments, vehicular mobility models and data traffic patterns. The results of FOTs can be used to update and enhance these models, such that large scale simulations based on real vehicle traces are possible.

However, in order to fully benefit from FOTs, academic researchers need to become familiarized with the potentials, the limitations, the benefits and the drawbacks of this new tool. In addition, since the money and resources to conduct large scale field trials are often not available to academic researchers, they must rely on and collaborate with industry and governmental institutions. Unfortunately, the goals of FOTs outcomes are not necessarily the same for vehicular manufacturers, road operators, and academic researchers.

It is therefore of essence that we learn how to successfully convey the benefits of giving academic researchers access to FOT data. If we compile a list of possible use cases for that, it will facilitate a request to collect a specific set of data and record the relevant meta data needed to achieve a certain goal and to enable reproducible results. Further, there is a need to better understand the goals and the interests of the different stakeholders in FOT from the beginning, so that motivations to tightly restrict access to field test data can be identified and addressed.

Generated data and the respective scenarios, comprising the conditions under which the data was collected, should be documented in detail so that all stakeholders are able to work with the information easily. Naturally, this entails that resources should be allocated already in project planning processes for data documentation as well as archival, maintenance, and distribution after the project.

In-depth, general purpose documentation can not only improve the flow of information from the stakeholders to third parties in academia. Traceability can also improve the exchange of knowledge from one (completed) FOT to another, something that is oftentimes relying on stakeholders active in both FOTs.

Due to the complexity of many large scale tests, we recommend that validation activities (e.g., using simulation or analytical methods) are planned for and integrated even during the early testing stages of a field trial. Furthermore, small scale tests ("dress rehearsals") should be conducted (preferably already in an early project phase) in order to test processes and data collection deeply as well as pre-evaluate results. This also includes the allocation of time periods used analyze and revise the system and experiment design before conducting the final experiments.

4.3.5 Conclusion

FOTs represent an enormous resource for the entire vehicular networking community and are of utmost importance for the development of IVC technology. While FOTs are mainly conducted by the automotive industry, the outcomes of such trials can be also of huge value for academia. The successful collaboration with third parties, however, poses some challenges.

In particular, the academic community should try to be more involved during the trial design phase and communicate the exact requirements for the collected data. Non-involved parties from both academia and industry can also hugely benefit from publicly available data, if all the needed meta data is logged and a general purpose documentation is included. This does not only allow for the development of better, more realistic analytical and simulation models but can also help conduct future FOTs.

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4.4 IVC Applications

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As a working group, the Applications Working Group discussed some key emerging issues related to different applications of VANETs in the market place. These discussions included safety, efficiency, and entertainment applications. Below, we provide a summary of the key issues discussed by the Applications Working Group

4.4.1 Why DSRC applications are not yet on the market?

The group felt that VANET research, in general, is at crossroads since there are some rumors and speculations that FCC might take back the 75 MHz bandwidth it had allocated to safety applications at 5.9 GHz in the last decade or so. To this end, FCC is considering to open up this bandwidth to the use WiFi for commercial applications which could complicate the overall picture considerably. The main reason for this appears to be the reluctance of car manufacturers to install DSRC radios in their vehicles due to cost considerations.

On the other hand, US Department of Transportation (DoT) has allocated about 100 Million USD for field trials in 6 different locations of the USA to demonstrate the huge benefits of using DSRC-equipped vehicles to safety. The field trial in Detroit, Michigan, for instance, was initially designed as an 18 months experiment and has been continuing for the last one year or so. It involves about 3000 drivers selected from different age groups, professions, education levels, gender, etc. in an effort to collect significant empirical data for demonstrating how the use of DSRC radios could increase the safety on the road (in urban areas and highways) significantly. The main motivation behind these massive field trials and the investment made by the US DoT is to collect convincing data (in a statistical sense) to present to the Congress for passing legislation for mandating the use of DSRC radios. If this effort succeeds, within couple of years one can hope to see DSRC radios installed in every car sold in the USA as a safety feature (similar to seat belts and air bags).

Another interesting development is the fact that several auto manufacturers are considering solutions based on cellular communications. As an example, General Motors (GM) has recently announced an agreement with AT&T to use AT&T equipment in their vehicles for Internet access and other services. This entails the use of an LTE modem installed in GM cars and the use of LTE (or LTE-A) networks of AT&T for several services. It is known that Mercedes-Benz and other car manufacturers are also considering similar solutions for providing different services to their customers. This new development, however, does not seem to prioritize safety as the key application. So, it remains unclear and very doubtful whether safety can be supported at a significant level with cellular communications.

Based on these developments, two major outcomes seem plausible:

- Based on the aforementioned field trials, assuming the collected data provide convincing evidence about the benefits of DSRC radios in reducing accidents and enhancing safety of driving, DOT passes legislation and pushes the car manufactures to use DSRC.
- DSRC applications are gradually introduced into the market place and more and more drivers install DSRC radios in their vehicles as they see the benefit. This will involve after-market DSRC devices for legacy cars and perhaps the installation of DSRC radios into only new high-end cars.

In both cases, however, there has to be convincing evidence that safety can be improved substantially via the use of DSRC technology. In this sense, the 6 field trials in the USA (and other similar large field trials in other parts of the world) will carry a lot of weight in providing reliable and significant data to the Federal Government and to the public.

At this juncture, viable business models might also be important in convincing the stakeholders to go ahead and mandate the DSRC technology. There was a general consensus that the 'golden triangle' for mandating the DSRC technology might be the government-car manufacturers-insurance companies, as the key stakeholders. However, these stakeholders have different objectives: for example, the US government's main objective is to reduce the 35,000 fatalities every year due to car accidents while the car manufacturers and insurance companies see the introduction of DSRC radios as merely another business transaction and by incorporating this new technology they would like to increase their profit margins (e.g., insurance companies could reduce/increase the premiums they charge depending on whether or not a car is equipped with a DSRC radio). While the cooperation of these stakeholders will clearly expedite the process, the role of the government in serving as a catalyst cannot be underestimated.

4.4.2 What can be done in academia?

It was noted by our group that the networking and communications people in VANET research should have a closer collaboration with the traffic safety people in the transportation domain (most of the current planning activity is done by these people and does NOT involve V2V or V2I communications) as these are the key people who determine how traffic planning is currently done and what are the underlying safety concerns. By better understanding their current thinking, the ongoing VANET research at universities could be more focused and direct in addressing the current needs and shortcomings of the existing system.

In going forward, it will also be important to convince automakers and drivers about the safety benefits of using DSRC technology. A conscientious and orchestrated effort in this direction could certainly contribute to the adoption of DSRC technology. However, as mentioned before, since the motivation of all car manufacturers is to make money and increase their profit margins, perhaps safety should not be the first application that our research should offer to automakers. Instead, perhaps other applications that DSRC technology can enable (such as efficiency and entertainment) should come first and safety should be tagged to these applications which might have potential as a revenue stream.

Another trend that was discussed is the growing interest in autonomous driving (AD). After the advent of Google's autonomous driving in Las Vegas and Nevada, some of the car manufacturers (such as GM, Nissan, Volkswagen, etc.) are heavily invested in R&D for autonomous driving. It is clear, however, that the autonomous vehicles so far do NOT emphasize the use of inter-vehicle communications (IVC) but, rather, rely on the presence of a very large number of sensors and actuators to 'sense' their environment and navigate accordingly, hence the name 'autonomous'. It was noted that this might change in the coming years as IVC should and probably will become a major component in autonomous vehicles as well. This is because an autonomous vehicle is ultimately a mobile robot and in decision making as a mobile robot its most challenging task is to make correct decisions at an intersection (especially at intersections which are not regulated with traffic lights or other traffic signals). It is clear that the rotating cameras, radars, and lidars that exist on autonomous vehicles are essentially LOS devices and cannot always discern objects (and other vehicles) which are on orthogonal roads at an intersection and, therefore, might be N-LOS. Our group decided that we should capitalize on this new trend and try to convince Google and other parties involved in autonomous driving about the huge benefits that could be reaped by the use of DSRC technology and IVC. So, a conscientious effort on how to integrate IVC to autonomous driving will be very timely and very helpful.

4.4.3 Cooperative Autonomous Driving

Continuing along this promising direction, potential new applications where integration of IVC with autonomous driving can be easily achieved were also discussed.

One application where autonomous driving would benefit from the presence of DSRC technology and IVC was identified as lane merging. All collaborative applications that require cooperation could also benefit from cooperative autonomous driving.

An interesting observation that was made is the fact that autonomous driving by definition is currently a local concept whereas integrating it with IVC could lead to large-scale benefits as it makes the autonomous vehicles much more aware of the state of the network.

Autonomous vehicles will be coming to the market place very slowly (presumably by 2020). Even then, we will probably observe a slow penetration rate due to cost issues as well as other issues (liability etc.). It is clear that many more vehicles can be equipped with communications capability and for less money before 2020, so autonomous vehicles can profit from other non-autonomous vehicles, but those that can communicate with the autonomous vehicles (if the autonomous vehicles are also equipped with DSRC radios). This provides yet another motivation for the integration of IVC with autonomous driving.

It is no secret that certain capabilities that make autonomous vehicles truly ‘autonomous’ are the massive and sometimes expensive sensors (such as rotating cameras on the roof of the Google autonomous vehicle, radars, lidars, etc.). Using DSRC radios might obviate the use of some of these expensive sensors in autonomous vehicles, thus reducing the cost of autonomous vehicles substantially which, in turn, will accelerate their massive adoption and use.

4.4.4 Definition of an “Application”

The last issue discussed in the Applications Working Group was the concern about lack of a common agreement on the definition of ‘an application’ when we approach things in a top-down manner. Different stakeholders see applications differently which create some ambiguity and undesired outcomes. How to resolve this issue does not seem very clear. As an example, is it correct to see vehicles as a computer/smartphone where applications can be downloaded ?

It was agreed that defining some common denominator about the definition of certain applications and their requirements (e.g., a safety application) would be very helpful. For example, it seems very difficult to influence what car manufacturers would like to see as an application. To take this example further: if different car manufacturers do not agree on the definition of safety (consider, for instance, the need for having situation awareness in vehicles as a safety application), then it might be very difficult to achieve concrete results on safety applications.

In going further, it will be crucial for car manufacturers to agree at a minimum level on the definition of an application (and its requirements). If this can be achieved, then third-party vendors can build upon those minimum requirements and promote new applications of IVC. It seems clear that here also the DoTs and the Federal Governments will have a crucial role to play.

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