

Inter-Vehicle Communication – Quo Vadis

Falko Dressler*, Hannes Hartenstein[†], Onur Altintas[‡], Ozan K. Tonguz[§]

*University of Innsbruck, Austria and University of Paderborn, Germany

[†]Karlsruhe Institute of Technology, Karlsruhe, Germany

[‡]Toyota InfoTechnology Center, Tokyo, Japan

[§]Carnegie Mellon University, Pittsburgh, PA, USA

Abstract—In September 2013, leading experts in Inter-Vehicle Communication (IVC) from all over the world met at the renowned Dagstuhl castle for a seminar discussing the question “Inter-Vehicular Communication – Quo Vadis?” The objective was to identify the current state of the art and, more importantly, the open challenges in R&D from both a 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 additional research in this field is necessary and if so, which will be the most intriguing and innovative research directions. It turned out that the overall perspective changed in the last few years, mainly as a result of the ongoing Field Operational Tests (FOTs) in the U.S. and in Europe. In this article, we report the key outcomes and results from the discussions pointing to new research directions and new challenges that need to be met for a second generation of vehicular networking applications and protocols. In particular, we present the reports and findings from the four working groups on scientific foundations of vehicular networking, Field Operational Tests, IVC applications, and heterogeneous vehicular networks.

I. INTRODUCTION AND MOTIVATION

The management and control of communication 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 Network (VANET), 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 field, namely vehicular networking, has emerged. There is a long list of desirable applications that can be grouped into four categories:

- safety 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 (at least while driving) and form factor constraints, and they might be always on.

On the other hand, due to high relative speeds, wireless communication may not be stable for a long time period and the network density is expected to vary from sparse to dense networks. Another challenging issue is the efficient use of available infrastructure, such as road side units or even cellular networks.

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 was organized on the topic of inter-vehicular communication. The motivation was to bring together experts in this field to investigate the state of the art and to highlight the existing solutions which adequately addressed some of the existing challenges. The main outcome of this inspiring seminar was to show 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 new research was still needed. These challenges have been summarized in [1].

We are now entering an era that might change the game in road traffic management. This is supported by the U.S. federal government announcement in February 2014 that National Highway Traffic Safety Administration (NHTSA) plans to begin working on a regulatory proposal that would require V2V devices in new vehicles in a future year.¹ This NHTSA announcement coincides with the final standardization of higher layer networking protocols in Europe by the European Telecommunications Standards Institute (ETSI).

It was the goal of this new 2013 Dagstuhl 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 adequate solutions exist today, where better alternatives need to be found, and also to provide guidance on where to look for such alternatives. Furthermore, the goal of this workshop was to go one step beyond and identify where IVC can contribute to the basic foundations of computer science or

¹<http://www.nhtsa.gov/About+NHTSA/Press+Releases/USDOT+to+Move+Forward+with+Vehicle-to-Vehicle+Communication+Technology+for+Light+Vehicles>

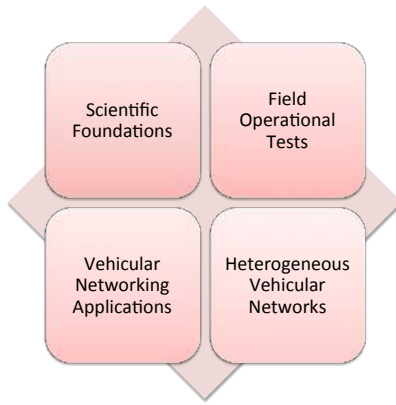


Fig. 1. Most important and challenging research fields identified

where previously unconsidered foundations can contribute to IVC.

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 (FOTs) have been conducted in the US (the Michigan field trial) as well as in Europe (simTD in Germany, DRIVE C2X in Europe). Our hypothesis was that lessons learned from those tests applied to currently used models and concepts would bring new insights into the forthcoming research challenges.

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 helped focusing on selected open research challenges. In addition, we also solicited ad-hoc presentations on topics of the working groups. The following working groups have been formed and led to interesting observations (cf. Figure 1):

- *Scientific Foundations* – In this group, one of the key questions discussed was to understand, which fundamental insights gained in the vehicular networking research domain can be transferred to other domains of computer science. The converse of this question 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 provide 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 Vehicular Networks* – As an important and

timely topic, the working group focused on the integration of different networking technologies. This is strongly needed for developing integrated IVC solutions and also for coping with early deployment problems like the initial low penetration ratio.

Eventually, all these questions converge on the fundamental issue of whether vehicular networking can now be shown to improve efficiency and safety on our streets.

II. SCIENTIFIC FOUNDATIONS

The working group on scientific foundations of 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 struggle 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 [2], 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 mis-behavior 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 [1]. Several research results appeared to have followed the proposed roadmap, see for example [3]–[5].

The working group then did a ‘gap analysis’, touching the following two issues: a) to what extent should IVC research ‘tailor’ a specific technology and b) should the interaction with other research communities be strengthened? We 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:

- *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 not surprising that maneuvering requires application protocols. However, group formation and dealing with the unreliable wireless channel opens up additional research questions.

- *Cognition and safety.* The cooperation with experts from intelligent vehicles area 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 [6]. Flexible and adaptable communication architectures can adjust to changing contexts, technologies and application mixes – this allows the system to evolve over time. This would also open a chance for building networks that go beyond IVC and would lead towards a broader 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.

III. BEST PRACTICES FOR FIELD OPERATIONAL TESTS

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 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 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 researchers in the scientific

field. From those discussions we distill recommendations for both researchers and trial operators to further improve the value and benefit of future field trials.

A. 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 Arbor² has been hosting about 3,000 vehicles equipped with Dedicated Short Range Communication (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 NHTSA rule making.

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 U.S. Department of Transportation (US DOT). 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 [7].

In Europe, the German simTD project [8] 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 [9] 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.

B. Benefits and Challenges of Using FOT Data

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

²http://www.its.dot.gov/safety_pilot/

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 not only network oriented FOTs (e.g., CAMP VSC3) but also more general ones (e.g., DRIVE C2X [9], simTD [8]) can therefore be extremely helpful to validate such models.

Not only can network models be improved with the help of field trials but they can also 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 [10].

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 research groups, even after the FOT has long been completed.

C. Recommendations

In order to fully benefit from FOTs, researchers need to be more involved with the potentials, the limitations, the benefits and the drawbacks of this new data generated at FOTs. In addition, since the money and resources to conduct large scale field trials are often not available to 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 researchers.

It is therefore essential that FOTs learn how to successfully convey the benefits of giving researchers access to FOT data. The community should compile a list of possible use cases for that, which 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 to analyze and revise the system and experiment design before conducting the final experiments.

IV. IVC APPLICATIONS

The IVC 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.

A. Why DSRC Applications Are Not Yet on The Market?

The group felt that IVC research, in general, is at crossroads since with the release of FCC NPRM 13-22 (Docket 13-49), the United States Federal Communications Commission has proposed allowing unlicensed devices such as Wi-Fi to share the 5.9 GHz ITS band, which is currently allocated for DSRC. To this end, FCC is considering to open up this bandwidth to the use of WiFi for commercial applications which could complicate the overall picture considerably.

On the other hand, the US 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. 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 new car sold in the U.S. 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, several OEMs have recently announced agreements with cellular carriers to use equipment from those specific carriers in their vehicles for Internet access

and other services. This entails the use of an LTE modem installed in cars and the use of LTE (or LTE-A) networks of carriers for several services. This new development, however, does not seem to prioritize safety as the key application.

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, US DOT passes legislation and mandates the use of DSRC equipment in new cars.
- 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 U.S. 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, while these stakeholders share the objective of social responsibility and acceptance of road traffic, they might not share a common view on how to share the risk that goes along with the introduction of a radically new communication network. The general impression was that the role of the government in serving as a catalyst cannot be overestimated.

B. What Can Be Done in Research?

It was noted that the networking and communications people in IVC 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 IVC research at universities could be more focused and directed to the current needs and shortcomings of the existing system.

A conscientious and orchestrated effort in this direction could certainly contribute to the adoption of DSRC technology. It was conjectured that perhaps safety should not be the first application that research should emphasize. Instead, perhaps other applications that are enabled by DSRC (such as efficiency and entertainment) should come first and safety should be tagged to these applications which might have better potential as a revenue stream.

Another trend that was discussed is the growing interest in autonomous driving. Several car manufacturers had for

years been pursuing R&D for autonomous driving. It is clear, however, that the autonomous vehicles so far do NOT emphasize the use of 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 line of sight devices and cannot always discern objects (and other vehicles) which are on orthogonal roads at an intersection and, therefore, might be non-line of sight. The group decided that one should try to convince parties involved in autonomous driving about the huge benefits that could be reaped by the use of Dedicated Short Range Communication / Wireless Access in the Vehicular Environment (DSRC/WAVE) technology and IVC. So, a conscientious effort on how to integrate IVC to autonomous driving will be timely and helpful.

C. Cooperative Automated Driving

Continuing along this promising direction, potential new applications were also discussed where integration of IVC with autonomous driving can be easily achieved. Lane merging was identified as one application where autonomous driving would benefit from the presence of DSRC technology and IVC. 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.

It is no secret that certain capabilities that make autonomous vehicles truly ‘autonomous’ are the massive and sometimes expensive sensors. 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, might accelerate their massive adoption and use.

V. HETEROGENEOUS VEHICULAR NETWORKS

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 fuzzy. This working group was formed 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.

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 HetNets. 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 802.11p DSRC (together with higher layer protocols such as WAVE or ITS G5), IEEE 802.11abgn consumer WiFi, and 3G/4G cellular networks.

A. Why Heterogeneous Networks

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’ satellite navigation 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 roll-out 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 [11], [12]. They might even in the long term 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 3G and 4G networks, coupled with multi-operator terminals, is a critical limitation [13].

The team identified two basic, opposing trends in heterogeneous vehicular networking that can be classified as follows (cf. Figure 2):

- *Class 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.
- *Class 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.

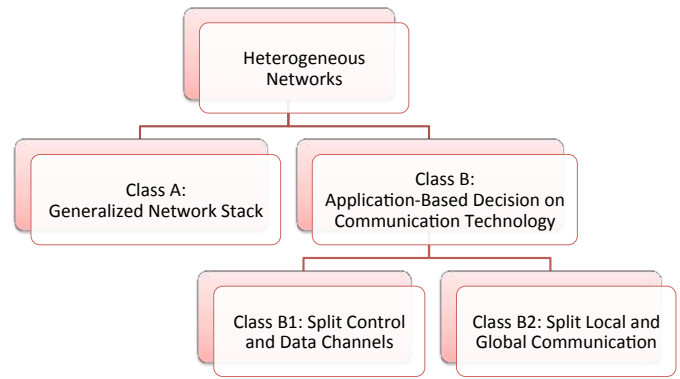


Fig. 2. Classification of heterogeneous vehicular networking approaches

B. 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 sparse networks, unhindered by network fragmentation or similar problems that would plague purely DSRC based solutions early after market roll-out.

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 previous work already explored cellular offloading, 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 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 [14].

C. 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 further into two sub-classes:

Class 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 [15], 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 [16].

Class B2 splits data according to a *local/global* decision. Local collaboration via DSRC/WAVE 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 [17], which employs short range radio for near field information exchange in clusters and cellular networks for interconnecting clusters.

D. Towards Heterogeneous Networks

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

- combining technologies with long-range and short-range coverage: they have different objectives but a positive effect 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 [18], [19];
- further investigation of offloading, scheduled downloading and relaying is needed, identifying promising use cases [20];
- continuing development of safety protocols and applications.

Heterogeneous Networks also imply a techno-organizational challenge of how to bring the diverse standardization bodies and committees together which are involved in the heterogeneous networking world of intelligent transportation. This issue goes along with the question of the ‘right layer’ for standardization, indicated in the above classification of approaches.

PARTICIPANTS

As organizers of such a seminar, we are completely dependent on the contributions and active participation of the seminar participants as well as on the helping hand of the whole staff of Schloss Dagstuhl. Contributing participants were (in alphabetical order); Natalya An, Claudio Casetti, Wai Chen, Falko Dressler, David Eckhoff, Andreas Festag, Raphael Frank, Mario Gerla, Javier Gozalvez, Marco Gruteser, Jérôme Haerri, Hannes Hartenstein, Geert Heijenk, Liviu Iftode, Stefan Joerer, Frank Kargl, Renato Lo Cigno, Giovanni Pau, Jonathan Petit, Björn Scheuermann, Florian Schimandl, Michele Segata, Christoph Sommer. Tessa Tielert, Ozan Tonguz, Elisabeth Uhlemann, and Peter Vortisch. Thanks to their enthusiasm and hard work, we were able to provide this report outlining many new insights and ideas.

REFERENCES

- [1] F. Dressler, F. Kargl, J. Ott, O. K. Tonguz, and L. Wischhof, “Research Challenges in Inter-Vehicular Communication - Lessons of the 2010 Dagstuhl Seminar,” *IEEE Communications Magazine*, vol. 49, no. 5, pp. 158–164, May 2011.
- [2] O. K. Tonguz, N. Wisitpongphan, and F. Bai, “DV-CAST: A distributed vehicular broadcast protocol for vehicular ad hoc networks,” *IEEE Wireless Communications*, vol. 17, no. 2, pp. 47–57, April 2010.
- [3] W. Klein Wolterink, G. Heijenk, and G. Karagiannis, “Constrained Geocast to Support Cooperative Adaptive Cruise Control (CACC) Merging,” in *2nd IEEE Vehicular Networking Conference (VNC 2010)*. Jersey City, NJ: IEEE, December 2010, pp. 41–48.
- [4] S. Joerer, M. Segata, B. Bloessl, R. Lo Cigno, C. Sommer, and F. Dressler, “To Crash or Not to Crash: Estimating its Likelihood and Potentials of Beacon-based IVC Systems,” in *4th IEEE Vehicular Networking Conference (VNC 2012)*. Seoul, Korea: IEEE, November 2012, pp. 25–32.
- [5] N. An, M. Maile, D. Jiang, J. Mittag, and H. Hartenstein, “Balancing the Requirements for a Zero False Positive/Negative Forward Collision Warnings,” in *10th IEEE/IFIP Conference on Wireless On demand Network Systems and Services (WONS 2013)*. Banff, Canada: IEEE, March 2013, pp. 191–195.
- [6] O. Tonguz and W. Viriyasitavat, “Cars as roadside units: a self-organizing network solution,” *IEEE Communications Magazine*, vol. 51, no. 12, pp. 112–120, December 2013.
- [7] M. Lukuc, “V2V Interoperability Project,” in *US DOT ITS Connected Vehicle Workshop*, Chicago, IL, September 2012.
- [8] H. Stübing, M. Bechler, D. Heussner, T. May, I. Radusch, H. Rechner, and P. Vogel, “simTD: A Car-to-X System Architecture for Field Operational Tests,” *IEEE Communications Magazine*, vol. 48, no. 5, pp. 148–154, May 2010.
- [9] R. Stahlmann, A. Festag, A. Tomatis, I. Radusch, and F. Fischer, “Starting European Field Tests for Car-2-X Communication: the DRIVE C2X Framework,” in *18th ITS World Congress and Exhibition*, Orlando, Florida, October 2011.
- [10] F. Dressler, C. Sommer, D. Eckhoff, and O. K. Tonguz, “Towards Realistic Simulation of Inter-Vehicle Communication: Models, Techniques and Pitfalls,” *IEEE Vehicular Technology Magazine*, vol. 6, no. 3, pp. 43–51, September 2011.
- [11] A. Vinel, “3GPP LTE Versus IEEE 802.11p/WAVE: Which Technology is Able to Support Cooperative Vehicular Safety Applications?” *Wireless Communications Letters*, vol. 1, no. 2, pp. 125–128, April 2012.
- [12] H. Rakouth, P. Alexander, A. Brown Jr., W. Kosiak, M. Fukushima, L. Ghosh, C. Hedges, H. Kong, S. Kopetzki, R. Siripurapu, and J. Shen, “V2X Communication Technology: Field Experience and Comparative Analysis,” in *FISITA World Automotive Congress*, vol. LNEE 200. Beijing, China: Springer, November 2012, pp. 113–129.
- [13] C. Sommer, A. Schmidt, Y. Chen, R. German, W. Koch, and F. Dressler, “On the Feasibility of UMTS-based Traffic Information Systems,” *Elsevier Ad Hoc Networks, Special Issue on Vehicular Networks*, vol. 8, no. 5, pp. 506–517, July 2010.
- [14] E. Yaacoub, F. Filali, and A. Abu-Dayya, “SVC video streaming over cooperative LTE/802.11p vehicle-to-infrastructure communications,” in *2013 World Congress on Computer and Information Technology (WCCIT 2013)*. Sousse, Tunisia: IEEE, June 2013.
- [15] B. B. Chen and M. C. Chan, “MobTorrent: A Framework for Mobile Internet Access from Vehicles,” in *28th IEEE Conference on Computer Communications (INFOCOM 2009)*. Rio de Janeiro, Brazil: IEEE, April 2009.
- [16] A. Baiocchi and F. Cuomo, “Infotainment services based on push-mode dissemination in an integrated VANET and 3G architecture,” *Communications and Networks, Journal of*, vol. 15, no. 2, pp. 179–190, 2013.
- [17] L.-C. Tung, J. Mena, M. Gerla, and C. Sommer, “A Cluster Based Architecture for Intersection Collision Avoidance Using Heterogeneous Networks,” in *12th IFIP/IEEE Annual Mediterranean Ad Hoc Networking Workshop (Med-Hoc-Net 2013)*. Ajaccio, Corsica, France: IEEE, June 2013.
- [18] B. Bloessl, M. Segata, C. Sommer, and F. Dressler, “Towards an Open Source IEEE 802.11p Stack: A Full SDR-based Transceiver in GNURadio,” in *5th IEEE Vehicular Networking Conference (VNC 2013)*. Boston, MA: IEEE, December 2013, pp. 143–149.
- [19] N. Haziza, M. Kassab, R. Knopp, J. Härrri, F. Kaltenberger, P. Agostini, M. Berbineau, C. Gransart, J. Besnier, J. Ehrlich, and H. Aniss, “Multi-technology Vehicular Cooperative System Based on Software Defined

Radio (SDR),” in *5th International Workshop on Communication Technologies for Vehicles (Nets4Cars-2013)*, vol. LNCS 7865. Lille, France: Springer, May 2013, pp. 84–95.

- [20] O. Altintas, K. Seki, H. Kremo, M. Matsumoto, R. Onishi, and H. Tanaka, “Vehicles as Information Hubs During Disasters: Glueing Wi-Fi to TV White Space to Cellular Networks,” *IEEE Intelligent Transportation Systems Magazine*, vol. 6, no. 1, pp. 68–71, January 2014.



Falko Dressler (dressler@ccs-labs.org) is a full professor of computer science at the University of Paderborn and still affiliated with the University of Innsbruck. Dr. Dressler is an Editor for journals such as *IEEE Trans. of Mobile Computing*, *Elsevier Ad Hoc Networks*, *ACM/Springer Wireless Networks (WINET)*, and *Elsevier Nano Communication Networks*. He was General Chair of *IEEE/IFIP WONS 2011* and *IEEE VNC 2014*, TPC Co-Chair for *IEEE VNC*, *IEEE VTC*, *ACM MSWiM*, and *IEEE GLOBECOM*, Area TPC Chair for *IEEE INFO-*

COM, and Poster/Demo Chair for *ACM MobiCom*. e regularly serves in the program committee of leading *IEEE* and *ACM* conferences. Dr. Dressler authored textbooks such as *Self-Organization in Sensor and Actor Networks*, published by *Wiley* in 2007. Dr. Dressler is an *IEEE Distinguished Lecturer* in the fields of inter-vehicular communication, self-organization, and bio-inspired networking. Dr. Dressler is a Senior Member of the *IEEE* as well as a Senior Member of *ACM*. His research activities are focused on adaptive wireless networking and self-organization methods with applications in wireless ad hoc and sensor networks, inter-vehicular communication, bio-inspired and nano-networking, and network security.



Hannes Hartenstein (hannes.hartenstein@kit.edu) is a full professor of computer science and a director of the Steinbuch Centre for Computing with the Karlsruhe Institute of Technology, Karlsruhe, Germany. He received a diploma in mathematics and a Ph.D. degree in computer science from Albert Ludwigs University of Freiburg, Freiburg, Germany. Prior to joining KIT he was a Senior Research Staff Member with *NEC Europe*. From 2001 to 2003, he was *NEC's* project leader for the *FleetNet-Internet on the Road* project and was involved in the *Network*

on Wheels (NOW) project during 2004-2008. He participated in the European Union Seventh Framework Programme (EU FP7) project *PRE-DRIVE-C2X* and is now actively involved in the EU FP7 project *DRIVE-C2X*. He is a coeditor of the book *VANET: Vehicular Applications and Inter-Networking Technologies* (*Wiley*, 2010), together with K. P. Laberteaux. His research interests include mobile networks, virtual networks, security, and information technology management. He was a general co-chair and a technical program co-chair for various *ACM* and *IEEE* workshops, conferences, and symposia related to wireless vehicular networks.



Onur Altintas (onur@jp.toyota-itc.com) is a fellow at the R&D Group of *Toyota InfoTechnology Center, Co. Ltd.*, in Tokyo. From 1999 to 2001 he was with *Toyota Motor Corporation* and was also a visiting researcher at *Telcordia Technologies*. From 2001 to 2004 he was with *Toyota InfoTechnology Center USA*. He received his B.S. (1987) and M.S. (1990) degrees from *Orta Dogu Teknik Universitesi*, Ankara, Turkey, and his Ph.D. (1995) degree from the *University of Tokyo*, Japan; all in electrical engineering. He is the co-founder and general co-

chair of the *IEEE Vehicular Networking Conference (IEEE VNC)*. He is an *IEEE VTS Distinguished Lecturer*.



Ozan K. Tonguz (tonguz@ece.cmu.edu) is a tenured full professor in the Electrical and Computer Engineering Department of *Carnegie Mellon University (CMU)*. He currently leads substantial research efforts at *CMU* in the broad areas of telecommunications and networking. He has published about 300 papers in *IEEE* journals and conference proceedings in the areas of wireless networking, optical communications, and computer networks. He is the author (with G. Ferrari) of the book *Ad Hoc Wireless Networks: A Communication-Theoretic Perspective*

(*Wiley*, 2006). In December 2010, he founded the *CMU* startup known as *Virtual Traffic Lights, LLC*, which specializes in providing solutions to acute transportation problems using vehicle-to-vehicle and vehicle-to-infrastructure communications paradigms. His current research interests include vehicular networks, sensor networks, wireless ad hoc networks, self-organizing networks, Internet of Things, smart grid, bioinformatics, and security. He currently serves or has served as a consultant or expert for several companies, major law firms, and government agencies in the United States, Europe, and Asia.