Research Challenges in Intervehicular Communication: Lessons of the 2010 Dagstuhl Seminar

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ABSTRACT

Intervehicle communication has become an extremely hot topic in networking research, opening up new research challenges well beyond those of classical mobile ad hoc network research. In October 2010, a Dagstuhl seminar has been organized bringing together many of the internationally leading experts in this field to discuss open issues and challenges related to IVC. This article reports the main findings of this meeting, that was set up to cover a wide range of topics. In particular, the following four areas were studied in working groups: Fundamental Limits and Opportunities of IVC, IVC Communication Principles and Patterns, Security and Privacy in IVC, and IVC Simulation and Modeling. A general conclusion drawn is that IVC is now at a turning point where the first-generation systems are engineered and will soon be brought to the market, while at the same time, IVC is experiencing the beginning of a new era characterized by a more fundamental research approach.

INTRODUCTION AND 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. In terms of vehicular ad hoc networks (VANETs), intervehicle communication (IVC), car-to-X (C2X), or vehicle-to-X (V2X), many interesting and challenging applications have been envisioned and (at least partially) realized. In this context, a very active research field has developed.

However, over the past few years, many researchers active in the field of IVC have started to ask themselves whether IVC is still a fertile field for basic and applied research or if it has become more a matter of industrial engineering (i.e., development). Looking at research projects worldwide, it seemed that the focus was clearly shifting toward leveraging the many research results to finally produce industrial products to be built into cars.

This motivated our idea to reconsider the topic from a research perspective, assessing what has been achieved, and — perhaps even more importantly — to discuss and identify where we have failed to provide sufficient answers yet. This approach should enable us to identify whether the discipline still provides important and yet unsolved challenges for basic and applied research and what those would be. By bringing leading researchers from around the world together and providing them with the right setting (and as few disturbances by email or other blessings of our modern world as possible), we hoped to be able to trigger this process.

In 2010, the authors of this article gathered around the idea of organizing such a meeting to discuss the future of IVC. In contrast to the many IVC-related conferences and workshops, the goal of this meeting was not to present research papers or outline the bright commercial future of this topic, but to broadly discuss open challenges and new research directions.

In the Schloss Dagstuhl — Leibniz Center for Informatics we found the perfect venue for this type of event. Dagstuhl offers modern facilities with a world-class computer science library and all modern amenities embedded into a historic building surrounded by a lovely countryside. Many meeting rooms of all sizes allows smaller ad hoc groups to retreat for discussions, and a famous wine cellar provides the perfect location for after-hour discussions, all complemented, for example, by a sauna, billiards, and free bicycles.

But what gives a Dagstuhl seminar its unique character, quite different from other scientific events? In general, organizers are requested to plan with only a minimum number of presentations but to maximize interactivity. In our case,

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we asked the invited researchers beforehand to submit ideas they wanted to discuss and performed a poll to see the interest in the various topics. From the results, we identified four working group topics and organized one invited talk per working group to provide initial stimulus for discussions. The remainder of the time was to be used for discussions and group work.

This article reports the key outcomes of the Dagstuhl Seminar on Inter-Vehicle Communication that took place from 3–6 October, 2010.

IVC AS WE SEE IT TODAY

While there are some similarities to research fields such as mobile ad hoc networks and wireless sensor networks, the specific characteristics of vehicular networks require different communication paradigms, different approaches to security and privacy, and 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 long time periods, and network density is expected to vary from sparse to very dense networks [1].

Another challenging issue is the efficient use of available infrastructure, such as roadside units and even cellular networks. Furthermore, IVC has strong links to other research domains, such as geo-informatics — as it requires very precise localization and precise maps — and highly scalable simulations required for analyzing traffic systems with hundreds or thousands of vehicles.

In the past years, many specific solutions for IVC have been designed, and at the time of writing, industry and other stakeholders are already calling for standardization. Nevertheless, we believe that many important research questions have only partially been 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 [2], transmit power control, and optimal medium access are just a few such issues.

The main goal of this seminar was to bring together leading researchers from both academia and industry to discuss and evaluate the state of the art, and highlight where sufficient solutions exist today and where better alternatives need to be found, and to give directions on where to look for such alternatives. Furthermore, one of our goals was to go one step beyond and identify where IVC can contribute to the basic foundations of computer science or where previously unconsidered foundations can contribute to IVC.

For example, IVC has triggered active research on reactive and dynamic security systems that do not try to provide security in a cryptographic sense at usually high costs, but create a tunable security-performance trade-off using reputation and consistency checking mechanisms that are not unlike human and social mechanisms to estimate trust in information. It remains to be seen if such mechanisms can be generalized and applied to other forms of networks that will be similarly dynamic and self-organizing in nature.

We organized four working groups on some of the most challenging issues in IVC:

- *Fundamental Limits of IVC*: The leading question of this working group was whether we can identify fundamental laws or limits that let us determine what IVC might achieve and what is not achievable using this kind of system.
- *IVC Communication Principles and Patterns*: This working group reviewed the current state of the art of communication patterns and principles in IVC systems.
- *Security and Privacy in IVC*: The focus of this working group was on topics related to security and privacy protection in IVC.
- *IVC Simulation and Modeling*: This working grouped focused on simulation-based evaluation of IVC and the necessary models.

The work was organized around daily topics: Day one should start with an introduction and a subsequent discussion on the current state of the art. On day two, the groups aimed at investigating specific challenges and discussed what a "VANET 2.0" would look like if those challenges were overcome. On day three, the goal was finally to identify a roadmap of how to get to this vision. The invited talks were scheduled on days one and two; each day ended with a plenary where the individual working group results were presented and discussed. On the final day, there was also room for short ad hoc talks to present recent ideas and current work.

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FUNDAMENTAL LIMITS OF IVC

This working group discussed whether communication theory, networking, and computer science could make fundamental statements about what IVC will be able to accomplish and where its limits are. Hannes Hartenstein from the Karlsruhe Institute of Technology highlighted this in his invited talk. Looking at safety and traffic efficiency applications, he raised the key questions:

- How many accidents and injured or killed people can be prevented by IVC?
- How much travel time and pollution can be saved when introducing IVC?

Examples for this are studies by Haas *et al.* on traffic safety [3] and Tielert *et al.* on carbon emission [4]. While these studies provide useful and valid data, and show that IVC will have an impact, they do not answer the question of whether this is the best we can get. Our assumption is that even a "perfect" IVC system will only have a limited effect on this. But have we reached these limits yet? Or can computer science at least help to identify where those limits are? Hartenstein pointed out that to approach this topic, various issues need to be addressed, such as taking driver behavior and the effect of IVC in car maneuvering into account. We also need to identify what "optimal traffic" would be and how to quantify it. Do we mean optimal traffic for the average or for individual drivers? Today, usually only one application per time is studied. How would many applications running in parallel influence each other's performance?

Answering such fundamental questions creates a strong need for a new kind of information

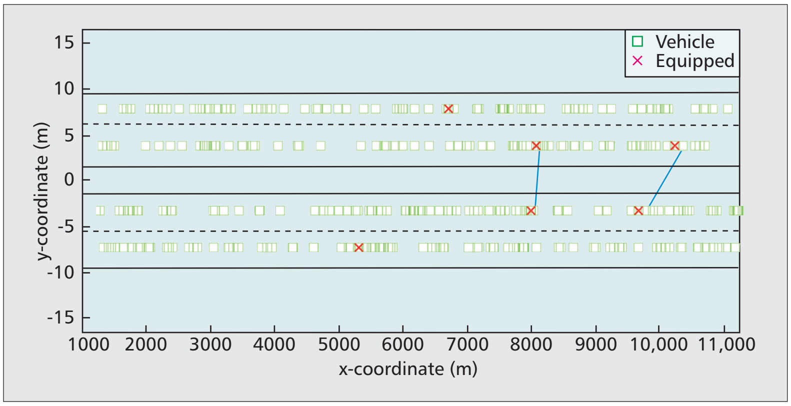

Figure 1. *Sparse communication scenario* (p = *0.02, transmission range 1 km).*

theory in the area of IVC. A good example is the recent work by Scheuermann *et al.*, who proved a fundamental limit for data aggregation in IVC [5]. Likewise, a control theory for distributed cooperative systems is yet to be developed. Even then, we still may be failed by our assumptions as disruptive technologies like full duplex radios [6] or surprising solutions to the hidden terminal problem might push the limits to areas we previously considered inaccessible.

The working group took up this input and started to work on a roadmap for a theoretical foundation of intervehicle communication. They pointed out inherent trade-offs between safety and efficiency in IVC-supported road traffic. These goals are not independent; for example, all accidents could be avoided if all cars came to a full standstill — this, though, is not efficient in terms of travel time. The working group therefore started to explore the "solution space" of IVC systems regarding safety on one hand and efficiency on the other, and to narrow it down by identifying infeasible regions.

The aim of such an approach would be to establish "upper bounds" on what IVC systems can possibly achieve with respect to both safety and efficiency gains under a given set of assumptions. The intuition is that a given IVC system is provably "good" if it comes close to such a bound.

To this end, the working group proposed to move from highly idealized and abstract models of IVC stepwise toward considerations that take more and more aspects into account. In practice, such an approach might start with assuming that each vehicle always has perfect and up-to-date knowledge about all other entities in the system. One would then have to establish what, under these assumptions, can possibly be achieved in terms of safety and traffic efficiency. Taking, say, information theoretic or control theoretic limits into account would further narrow down the feasible region. If proposed applications and protocols come close to thereby established limits, this shows that they make full use of IVC's potential. Finally, it would also be interesting to compare IVC benefits to what can possibly be achieved with non-cooperative technologies that only rely on local sensors, as this might provide a rigorous justification for the use of communication technology in road traffic.

Intervehicle Communication Principles and Patterns

Ozan K. Tonguz from Carnegie Mellon University introduced the topic of "Inter-Vehicle Communication Principles and Patterns" in his invited talk, where he pointed out the relationship between the characteristics of the communication system and propagation models on one hand and the profound effect this has on performance metrics of IVC applications on the other (e.g. penetration, distance, or end-to-end delay) [7, 8]. As a conclusion, he stressed the importance of cross-layer design in IVC.

In the second part of his talk, Tonguz discussed emerging IVC applications such as safety, traffic information systems, and entertainment, and the underlying communications principles and paradigms. In particular, he elaborated on how vehicle-to-vehicle (V2V) communications can be used as a major enabler for ubiquitous traffic control [9]. This self-organized traffic control paradigm, co-invented by Tonguz and Ferreira and their students in 2009, can increase traffic flows in urban areas by about 60 percent during rush hours, which seems pretty significant as such an improvement translates into mitigating congestion, reducing the commute time of workers during rush hours, lessening the carbon footprint of cars, supporting a greener environment, and increasing productivity. He suggested that such colossal benefits may be harvested in the next 10 years thanks to V2V communications. In realizing such huge benefits, the adoption of dedicated short-range communication (DSRC) technology by different governments (and departments of transportation) will clearly play a major role, and Tonguz highlighted the significant role of public policy decisions and new legislation in different countries in accelerating this process.

The working group discussions started with a review of the state of the art in different communication technologies like cellular (Long Term Evolution [LTE], LTE-Advanced [LTE-A]) and DSRC (IEEE 802.11p) that can be applied in IVC scenarios. An important conclusion was that, in the future, cellular and ad-hoc communication technologies for IVC might be viewed as complementary technologies instead of competing ones. A major research challenge is therefore the design of communication systems and protocols, which can combine both forms of communication in an intelligent way — transparent to IVC applications.

The participants also discussed the important role of one-hop broadcast in IVC and that neither of the current technologies was designed primarily for this purpose. The communication conditions in IVC networks are extremely challenging, particularly due to the rapidly changing nature of the network with increasing penetration of IVC technologies. In sparse communication scenarios, as shown in Fig. 1, in most cases vehicles can only communicate via 1-hop broadcast with vehicles driving in the opposite direction. Therefore, a communication pattern making use of the carriage of data aboard a moving vehicle as one element of forwarding is required [10]. In contrast, a dense communication scenario, as shown in Fig. 2, allows the forwarding of data along multiple hops directly via the wireless link. Therefore, adaptive schemes are needed to overcome this gap. There is a lot of potential for enhancement in developing one-hop broadcasting or beaconing schemes for IVC in highly dynamic environments, a good example being the Adaptive Beacon Protocol (ATB) [7].

Since IVC deployment will take several years to achieve significant market penetration, initial deployment should focus on simple applications that can be deployed fast. This implies that they can cope with sparse communication scenarios and use simple, delay-tolerant data dissemination schemes. Furthermore, although IVC has advantages for localized solutions and services, in the initial deployment phase cellular technologies such as LTE can be used to overcome situations where no vehicle equipped with DSRC radios is within the transmission range.

While current research discusses IVC mostly in the context of V2V communications, it might be beneficial to look at larger systems involving trucks, buses, cyclists, pedestrians, and even animals. Combining different communications technologies from WiMAX to radio frequency identification (RFID) will inevitably lead to highly heterogeneous networks with a broad range of communication types. How to handle such a heterogeneous network environment appears to be an important and open research problem.

Finally, there is also a strong interrelation between applications and the forms of communications, and advancement in one field will always trigger new developments on the other side. However, the key driver should be the applications, as only they will in the end provide a benefit for the drivers or passengers.

Security and Privacy

Security and privacy protection are still considered to be among the major challenges for IVC. While significant work has been done in this area over the past years, the very nature of IVC makes it extremely challenging to come up with a satisfying security and privacy solution. The goal of the security and privacy working group was to provide a judgment on the status of various security and privacy related issues, and discuss some solutions for still open questions.

Initial discussions in the working group were based on issues raised by Elmar Schoch from Volkswagen in his invited talk. He stressed that for security and privacy protection, it is essential that we find the right level of protection. If we overdo security, this might negatively affect application performance and reduce IVC benefits in general. If the security or privacy protection provided is too low, the security or privacy incidents that occur will likely result in reduced trust of drivers in IVC systems, and might thus severely damage deployment. From a manufacturer's point of view, cost also plays a very important role.

The discussion also touched on the status of current security mechanisms, and whether they are ready and sufficient for an initial IVC deployment. To answer this question, the participants created an overview map of research topics and issues, shown in Fig. 3.

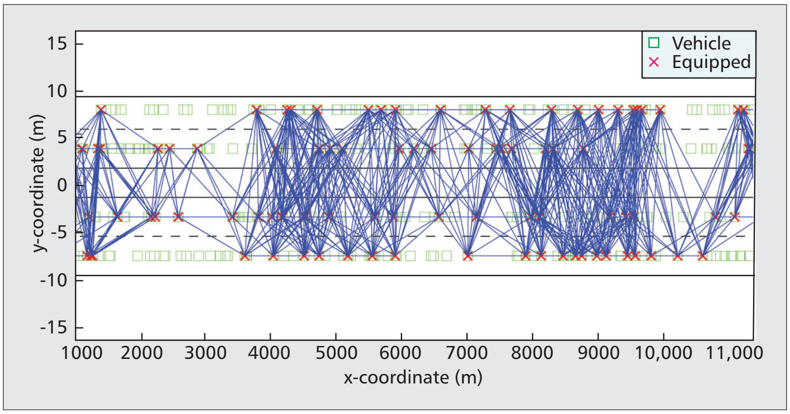

Figure 2. *Dense communication scenario (*p *= 0.30, transmission range 1 km).*

The topics are grouped into the main IVC security domains: *ID management and message authentication*, *privacy protection*, *data consistency*, and *in-vehicle security*. The topics within these categories are not meant to be exhaustive but should give a broad overview of various issues that are covered in the literature and discussed at scientific conferences and in standardization bodies. Topics are marked in green if a number of proposals are available in the literature, and there is general agreement among researchers and in standardization bodies on which mechanisms to include for a first deployment of IVC security and privacy. Yellow indicates topics where there is a large variety of proposed security or privacy protection mechanisms in the literature, but a consensus on how to solve this problem has not yet been reached. Topics in red indicate issues that are still unsolved and where only a few works are available so far.

An example of a topic where there is general agreement is the use of elliptic curve cryptography (ECC)-based asymmetric cryptography for message authentication and integrity protection using public-private key pairs and certificates issued by a public key infrastructure (PKI) [11]. A matter of ongoing discussion is, however, how vehicles would communicate with the PKI for certificate renewal (which happens especially often whenever pseudonyms are employed): can a third-generation (3G) connection be assumed to be present for this, or do more sporadic communication channels have to suffice?

One topic of particular importance is avoiding the overhead associated with secure broadcast communication, and achieving scalable and efficient authentication of broadcast mechanisms. The ultimate goal of applying security mechanisms to IVC is to ensure correctness of communicated data. That is, no attacker should be able to disseminate forged data in the network. Ensuring trust and integrity of packets as achieved with a *key-pair–certificate–signature* solution is only one part of the solution, and one that comes with very high overhead [12]. There are many proposed alternatives, some using symmetric instead of asymmetric cryptography [13], *The big challenge will be to find the right trade-off between strong security and privacy protection on one hand and efficiency and low overhead on the other. If researchers and developers fail in either direction, it will inevitably lead to problems with either vulnerable or inefficient and unusable systems.*

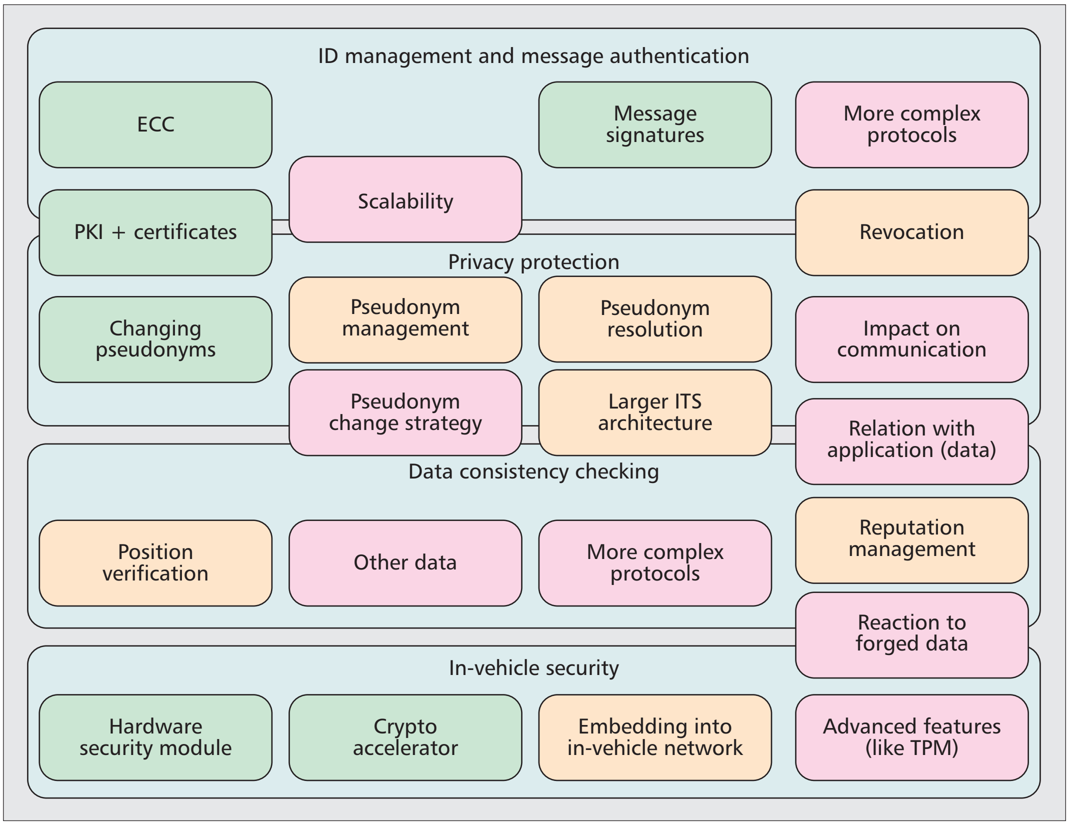

Figure 3. *Research topics in IVC security and privacy.*

or hybrid solutions that use asymmetric or group cryptography only for distribution of symmetric keys. However, most of these solutions come with significant drawbacks; therefore, the mainstream solution under discussion still relies on a key-pair–certificate–signature scheme.

During the working group sessions, participants discussed additional ways of achieving efficient broadcast communication that require additional refinement and discussion after the seminar. Beyond the integrity and authenticity protection achieved by key-pair–certificate–signature, a further conclusion was that data consistency needs to be guaranteed by additional mechanisms that cross-validate data received from various sources that an attacker cannot influence in parallel. Overall, the discussions in the security working group provided a good overview on the current situation of security and privacy in IVC. While there is no complete solution and agreement on all matters, the participants concluded that the major questions to be solved are clear, and at least some are answered sufficiently. The big challenge will be to find the right trade-off between strong security and privacy protection on one hand and efficiency and low overhead on the other. If researchers and developers fail in either direction, it will inevitably lead to problems with either vulnerable or inefficient and unusable systems.

IVC Simulation and Modeling

This working group was bootstrapped by a joint invited talk given by Martin Treiber from the Technical University of Dresden and Christoph Sommer from the University of Erlangen-Nürnberg, concentrating on issues of traffic modeling and integrated simulation, respectively. Christoph Sommer focused on three central questions:

- How can the huge variety of different models (channel, traffic, driver, communication) be assembled into one consistent simulation?
- How can such simulations capture truly heterogeneous networks and scenarios?
- How can one abstract from fine-grained communication models to achieve scalable simulations that still provide accurate results?

While Christoph Sommer concentrated on communication models, Martin Treiber looked at the issue of traffic flow models and how they can be applied to evaluate congestion warning systems, traffic flow assistants, and traffic light assistants. He stressed that traffic flow models are especially important for evaluating the accuracy and effects of traffic efficiency applications, and showed how analytical information models can be tested against microsimulations and real trajectory data. For simulations done with low penetration rates, the comparison of results shows promising results, revealing only small discrepancies if road traffic microsimulation is tightly coupled with network simulation [14, 15].

In the working group, the participants continued along this line of discussion and also looked into the complexity of models. General agreement was reached that complex models with too many input parameters (e.g., for radio channels)might not be too useful, as it might be hard to determine the right settings for those parameters.

As for cross-cutting aspects, both the Limits and the Simulation working groups questioned whether we already have the metrics to assess those limits. One aspect would be better channel models and to predict how future receivers would handle effects like Doppler-shift or multi-path propagation. Others would include evaluation metrics such as the CO_2 footprint or the impact of human driver behavior. However, regarding analytical channel models, Hartenstein quoted Raj Jain, stating *"In general, analytical modeling requires so many simplifications and assumptions that if the results turn out to be accurate, even the analysts are surprised."* So better cross-validation of analysis, simulations, and measurements is needed to prove the validity of the models in different IVC situations.

The discussion in this working group focused mainly on questions related to the complexity of the used models that, independent from each other, achieved very accurate results. However, in combination, it is still unclear to what extent reality can be reproduced to evaluate qualitative and quantitative aspects of large-scale IVC systems.

SUMMARY AND CONCLUSION

Looking at the seminar as a whole, we think there are two important observations, one more general and one more IVC-specific. The general observation, which has been validated in a countless number of these Dagstuhl seminars over the last years, is that to boost scientific creativity, there is no replacement for putting a bunch of enthusiastic researchers into a room, getting rid of disturbing factors, and letting them think and discuss.

More specifically, on the topic of IVC, it became clear that IVC is still a vibrant topic with many challenges ahead of us. At the same time, we are at a turning point where a first generation of standards and products is designed and brought to the market. Industry and many research projects now aim for very practical evaluation of IVC systems in field tests. For this to succeed and provide meaningful results, our approach to evaluation needs to focus more on the application benefits of IVC, not only on network properties. In the end, the success of IVC will be measured in prevented accidents or reduced carbon emissions, not in packet delivery ratio. Looking at the recent literature, this change is already happening now, but work on better support in evaluation tools like simulators is clearly needed.

As far as the fundamental limits of intervehicle communication systems are concerned, we are facing the fact that current information and control theory are not suitable to be directly applied to those dynamic, decentralized, and broadcast-based IVC systems. Working toward a better theoretical foundation for IVC could also benefit other areas that face similar challenges.

In terms of intervehicle communications principles and patterns, one lesson learned was to emphasize a cross-layer design approach whereby the developed communication protocols and applications are cognitive of the agile and challenging physical layer conditions in vehicular networks. It was also observed that vehicle-to-vehicle communications can be used as a major enabler for providing radical improvements in mitigating congestion, reducing commute time of urban workers, supporting a greener environment, decreasing the carbon footprint of cars, and increasing productivity. To enable some of these solutions for large-scale transportation problems, new public policies or legislation at the government level will be important for mandating DSRC technology. Given this outlook, another conclusion drawn was that in the initial stage of DSRC deployment, the communications and networking paradigms developed for different applications in vehicular ad hoc networks should utilize existing mature cellular technologies such as 3G, LTE, and LTE-A.

Security and privacy still provide a multitude of challenging questions. While research efforts have produced constant progress, there is still a way to go before coming up with an exhaustive solution due to the fundamentally different nature of security and privacy challenges in IVC compared to traditional networks.

Accurate and realistic simulation and modeling of IVC protocols and applications are the basis for almost all developments in this area. As field tests are always limited in size and scope, basic research in IVC relies on analytical models and simulation. Much progress can be seen in various aspects such as the development of adequate mobility models, the use of more precise metrics besides classical networking aspects, and even the modeling of non-technical parameters such as human driver behavior. More insights are needed to study those aspects in a holistic way.

In the end, the success of IVC will be measured in prevented accidents or reduced carbon emissions, not in packet delivery ratio. Looking at the recent literature, this change is already happening now, but work on better support in evaluation tools like simulators is clearly needed.

PARTICIPANTS

As organizers of such a seminar, we are completely dependent on the contributions and active participation of the seminar participants. We therefore want to express our sincere thanks to the participants of the Dagstuhl Seminar on Inter-Vehicular Communication. Due to their enthusiasm and hard work, we were able to provide this report outlining a lot of new insights and ideas.

Fundamental Limits of IVC were explored by Hannes Hartenstein, Geert Heijenk, Martin Mauve, Björn Scheuermann, and Lars Wolf. The Communication Patterns WG was composed of Claudio Casetti, Falko Dressler, Lars Eggert, Felix Schmidt-Eisenlohr, Jérome Härri, Ozan Tonguz, and Lars Wischhof. Security and privacy issues were the focus of Levente Buttyan, David Eckhoff, Frank Kargl, Panagiotis Papadimitratos, and Elmar Schoch. The Simulation and Modeling group included Stefan Laemmer, Jens Mittag, Felix Schmidt-Eisenlohr, Jörg Ott, Christoph Sommer, and Martin Treiber.

Finally, we want to thank Annette Beyer, Roswitha Bardohl, and the whole staff of Schloss Dagstuhl for being the perfect hosts for our seminar.

While research efforts have produced a constant progress, there is still a way to go before coming up with an exhaustive solution due to the fundamentally different nature of security and privacy challenges in IVC compared to traditional networks.

References

[1] O. K. Tonguz, N. Wisitpongphan, and F. Bai, "DV-CAST: A Distributed Vehicular Broadcast Protocol for Vehicular Ad Hoc Networks," *IEEE Wireless Commun.*, vol. 17, no. 2, Apr. 2010, pp. 47–57.

[2] E. Schoch *et al.*, "Communication Patterns in VANETs," *IEEE Commun. Mag.*, vol. 46, no. 11, Nov. 2008, pp. 2–8.

[3] J. J. Haas and Y.-C. Hu, "Communication Requirements for Crash Avoidance," *7th ACM Int'l. Wksp. Vehicular Inter-Networking (VANET 2010)*, Chicago, IL: ACM, 2010, pp. 1–10.

[4] T. Tielert *et al.*, "The Impact of Traffic-Light-to-Vehicle Communication on Fuel Consumption and Emissions," *Internet of Things 2010*, Tokyo, Japan, Nov. 2010.

[5] B. Scheuermann *et al.*, "A Fundamental Scalability Criterion for Data Aggregation in VANETs," *ACM MobiCom 2009*, Beijing, China, Sept. 2009.

[6] J. I. Choi *et al.*, "Achieving Single Channel, Full Duplex Wireless Communication," *ACM MobiCom 2010*, Chicago, IL, 2010, pp. 1–12.

[7] C. Sommer, O. K. Tonguz, and F. Dressler, "Adaptive Beaconing for Delay-Sensitive and Congestion-Aware Traffic Information Systems," *IEEE VNC 2010*, Jersey City, NJ, Dec. 2010, pp. 1–8.

[8] M. Boban *et al.*, "Impact of Vehicles as Obstacles in Vehicular Ad Hoc Networks," *IEEE JSAC*, vol. 29, no. 1, Jan. 2011, pp. 15–28.

[9] M. Ferreira *et al.*, "Self-Organized Traffic Control," *ACM VANET 2010*, Chicago, IL, Sept. 2010, pp. 85–89.

[10] L. Wischhof, A. Ebner, and H. Rohling, "Information Dissemination in Self-Organizing Intervehicle Networks," *IEEE Trans. Intell. Transportation Sys.*, vol. 6, no. 1, Mar. 2005, pp. 90–101.

[11] P. Papadimitratos *et al.*, "Secure Vehicular Communications: Design and Architecture," *IEEE Commun. Mag.*, vol. 46, no. 11, pp. 2–8, Nov. 2008.

[12] E. Schoch and F. Kargl, "On the Efficiency of Secure Beaconing in VANETs," *ACM WiSec 2010*, Hoboken, NJ, 2010, pp. 111–16.

[13] Y.-C. Hu and K. P. Laberteaux, "Strong Vanet Security On A Budget," *4th Annual Conf. Embedded Security in Cars,* Berlin, Germany: Is-Its, Nov. 2006.

[14] M. Treiber, A. Hennecke, and D. Helbing, "Congested Traffic States in Empirical Observations and Microscopic Simulations," *Phys. Rev. E*, vol. 62, 2000, p. 1805.

[15] C. Sommer, R. German, and F. Dressler, "Bidirectionally Coupled Network and Road Traffic Simulation for Improved IVC Analysis," *IEEE Trans. Mobile Computing*, vol. 10, no. 1, pp. 3–15, Jan. 2011.

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