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INVITED PAPER

Cooperative Driving and the Tactile Internet

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ABSTRACT | The trend toward autonomous driving and the recent advances in vehicular networking led to a number of very successful proposals in cooperative driving. Maneuvers can be coordinated among participating vehicles and controlled by means of wireless communications. One of the most challenging scenarios or applications in this context is cooperative adaptive cruise control (CACC) or platooning. When it comes to realizing safety gaps between the cars of less than 5 m, very strong requirements on the communication system need to be satisfied. The underlying distributed control system needs regular updates of sensor information from the other cars in the order of about 10 Hz. This leads to message rates in the order of up to 10 kHz for large networks, which, given the possibly unreliable wireless communication and the critical network congestion, is beyond the capabilities of current vehicular networking concepts. In this paper, we summarize the concepts of networked control systems and revisit the capabilities of current vehicular networking approaches. We then present opportunities of Tactile Internet concepts that integrate interdisciplinary approaches from control theory, mechanical engineering, and communication protocol design. This way, it becomes possible to solve the high reliability and latency issues in this context.

KEYWORDS | Cooperative adaptive cruise control (CACC); cooperative driving; real-time guarantees; Tactile Internet

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I. INTRODUCTION

We are currently experiencing astonishing developments in the field of wireless communications. Since the early days of WiFi and 2G/3G networks, data rates went up two to four orders of magnitude from a few kilobits per second (2G) or a few megabits per second (WiFi, 3G) to now more than a gigabit per second. This trend still continues and we see novel wireless communication technologies at the horizon mainly focused on providing big data pipes. In the field of short-range wireless, WiFi includes now IEEE 802.11ac [1] and in the cellular world, and we see first (trial) deployments of 5G networks [2]. We anticipate that these advances will continue to speed up our wireless networks in the coming years; yet, data rates alone are not sufficient.

Orthogonal to these huge data pipes, there is the need for improvements in other directions. Given the widespread availability of wireless communication technology, interest has grown to apply this to either previously wire dominated fields (e.g., industry automation) as well as to completely new application domains (e.g., connected cars). The main emphasis in these areas is on ultralow latency and very high reliability. With these objectives in mind, the Tactile Internet initiative has been formed [3], [4]. The name Tactile has been coined with applications on remote haptics in mind. This includes distributed robot control, remote surgery, coordinated automated driving, and many other cyber–physical system (CPS) solutions. In summary, we can describe most of these applications as networked control solutions, where local control is influenced by remote sensors or actors and even human players in the loop, the latter one introduced by the research area of cyber–physical social systems (CPSS) [5].

We concentrate on one of the prime application domains of the Tactile Internet: cooperative automated driving. Research in this field is driven by two main technologies: vehicular networking and automated driving. We concentrate on the communications part that is often also referred to as vehicular *ad hoc* network (VANET) or, more recently, car-to-car communication [6]. The fundamental basis of VANETs is the use of IEEE 802.11p-based communication stacks [7], which are fully relying on the CSMA/CA-based medium access. In particular, we are talking about IEEE WAVE/1609 [8] in the United States, ETSI ITS-G5 [9] in Europe, and ARIB T109 [10] in Japan. Following results from early field trials, these communication stacks have been extended to primarily support very large numbers of cars by introducing congestion control mechanisms. The European Decentralized Congestion Control (DCC) solution [11] is now also incorporated into the U.S. IEEE WAVE stack. However, little priority has been put on guarantees for low latency communication or certain degrees of reliability. This is currently changing with the introduction of cooperative automated driving applications.

Bringing both research domains, i.e., cooperative driving and the Tactile Internet, together, we see not only a perfect fit but also a strong need for introducing these concepts as enablers for future cooperative automated driving solutions. Looking from an automated driving perspective, we are essentially concerned with vehicle dynamics and control [12]. Cooperative adaptive cruise control (CACC)-based platooning [13] is the prime example for large scale distributed control applications in this field, where local dynamics and control influence an entire set of cars that need to be coordinated and controlled as a whole in order to avoid crashes [14]. Having said that, the two main objectives of Tactile Internet research are also the most important ones for platooning: high communication reliability and low latency. These two objectives are essential to guarantee the bounds that ensure safety, which are much more important than elegant optimal solutions that cannot incorporate systems impairments.

In this paper, we address the need for such bounds and guarantees taking cooperative driving as an example application. We investigate how such time critical communication can be realized in this field and also derive open research challenges that need to be addressed by our entire research community. The remainder of this paper is structured as follows. In Section II, we briefly revisit current vehicular networking solutions that build the basis for cooperative driving maneuvers. In Section III, we discuss CACC-based platooning concepts, the underlying control problem, and its current not yet satisfying implementations using IEEE 802.11p-based protocols. In Section IV, we introduce two possible ways out of this dilemma, looking at Tactile-Internet-based solutions using either integrated network/control concepts or heterogeneous networking technologies, which are eventually complementary to each other. We conclude the paper highlighting relevant open research challenges in Section V.

II. VEHICULAR NETWORKING: A RETROSPECTIVE VIEW

After more than 15 years of research in vehicular networking, research evolved from pure theoretical studies up to large scale field tests, and today to the first deployed systems in newly sold vehicles. A first and still very important application domain for vehicular networks has been cooperative awareness: cooperative awareness messages are broadcast to inform neighboring nodes about a vehicle's current status, i.e., position, speed, acceleration, heading, etc.; this process is also called beaconing. These small 1-hop broadcasts help improving road traffic safety and efficiency [6], [15]. In the past, several protocols have been proposed starting with fixed period beaconing [16], adaptive beacon interval selection [17]–[21], and to coordinated use of multiple channels [22], [23] for improved performance in highly congested road traffic scenarios.

SOTIS [16] proposes the usage of a knowledge base for a self-organizing traffic information system. Selected knowledge base items are periodically transmitted to local neighbors at a fixed time interval. Evaluations showed that such static period beaconing is not suitable for every traffic scenario (too slow for spare traffic, too fast for dense traffic). Protocols such as REACT [17] and ATB [18] investigated adaptive beaconing approaches, in which the interval between two consecutive beacons is adapted according to the traffic density. The primary goal is to send information as often as possible, but avoid overloading the wireless channel at any time. This has further been extended to include receiver centric metrics in FairDD [24], as in realistic road traffic networks, a potential receiver could be interested in different information items than a sender. The concept therefore aims at maximizing the overall transmitted message utility. For congestion control, FairDD has been integrated with ATB. The resulting FairAD [25] concept thus provides a resilient communication protocol for vehicular networks.

Standardization bodies picked these research findings on beaconing protocols up and developed communication stacks for vehicular communications. In Europe, this is the ETSI ITS-G5 protocol suite, which also introduces DCC to not overload the wireless channel. In particular, the channel load is constantly monitored and the standard defines a dedicated state machine to control beacon interval, transmit power, transmit data rate and sensitivity according to the currently perceived load. In the United States, the IEEE 1609 protocol suite also offers multichannel operation (IEEE 1609.4), security services (IEEE 1609.2), routing and message dissemination (IEEE 1609.3), as well as resource management (IEEE 1609.1). Congestion control is currently being added based on the LIMERIC approach [19]. The basis for both standards is the IEEE 802.11p protocol which is based on wireless local area network (WLAN) and defines both physical layer (PHY) and medium access control (MAC) using a dedicated spectrum in the 5.9-GHz band.

On the other hand, cellular communication based on 4G incorporating long-term evolution (LTE) and LTE device-to-device (D2D; infrastructure supported *ad hoc* communication) is getting keen attention to be used as another vehicular communication technology [26]. In particular, the recent development of LTE vehicle-to-everything (V2X) focuses on the requirements of vehicular communications and their challenges concerning the high mobility of nodes in the network [27]. LTE V2X is based on LTE D2D, which allows nodes to communicate directly without relaying data over the base station (eNodeB) having the benefit of lowering the channel load and the ability for spatial reuse of the frequency spectrum. LTE D2D specifies two modes for channel allocation, one requiring central infrastructure and one fully distributed channel resource allocation without the need of any infrastructure.

Recent research investigations also consider other technologies than IEEE 802.11p as a feasible medium for communication between vehicles, and between vehicles and roadside units (RSUs). One prominent candidate is visible light communication (VLC), for which the existing head and tail lights of vehicles can be used to transmit information [28]–[30]. The receiving part in VLC can either be a photodiode or a camera-based system [31]. Another candidate is millimeter-wave (mmWAVE) which takes advantage of the spectrum between 30 and 300 GHz [32]. However, both technologies, VLC and mmWAVE, depend on good channel characteristics due to their high frequency and requiring line-of-sight (LOS) links to reach good performance. First evaluations of VLC show that it is feasible for outdoor communication in the vehicular context [33], [34].

Having all the mentioned communication technologies in mind, we believe that the real question is not *which* technology will be used for future vehicular networks, but *how* all these technologies should be combined and orchestrated to fully optimize the information flow through intelligent road traffic networks. These different communication techniques should be combined to fully exploit their potential, and go one step beyond 5G. This is in particular needed to support the requirements for future wireless networks incorporating the Tactile Internet and cooperate driving, meaning low latency, high throughput, and high reliability and dependability by providing full availability of the communication links when they are needed.

From the protocol design perspective, algorithms for message dissemination need to move away from providing functionality only for a single application domain. Having realistic scenarios in mind, many different applications need to communicate with neighboring vehicles at the same time. The dominating communication primitive is broadcasting, even though the mentioned application requirements still need to be considered.

In [35], a class-based and context-aware broadcasting scheme is proposed to support past and future application domains by abstracting application layer functionality from message forwarding logics. We believe that this helps to further gain performance in vehicular networks as it avoids dissemination of redundant information, and gives applications the possibility to be operated concurrently on a wireless network avoiding negative impacts of each other. The primary goal is to classify applications into four different categories as outlined in Fig. 1. Here, *Class A* specifies simple 1-hop broadcasts for cooperative awareness and building 2-hop neighbor information which serves as a fundamental basis for Class B/C/D. *Class B* is using this 2-hop neighbor information to disseminate important information among all direct and indirect (2-hop) neighbors; possible applications for this type of broadcast class are intersection collision avoidance or precrash warning. *Class C* performs broadcasting with geographic constraints, e.g., along a road segment to inform nodes about an approaching emergency vehicle. Finally, *Class D* supports low priority geocasting of information elements maintained in knowledge bases, similar to epidemic forwarding of information related to geographic regions and interest of receivers to disseminate information, e.g., about traffic conditions or warnings about a wrong way driver. Each of these classes implements a set of protocols to be used to perform the needed data dissemination schemes according to the actual traffic situation, node density, and application requirements. This fundamental paradigm change of network protocol design is an important step toward deploying a heterogeneous set of applications while maintaining all safety related performance metrics.

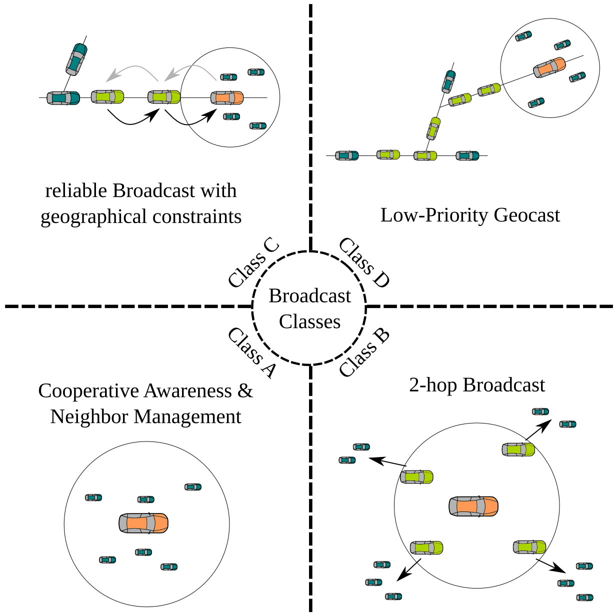

Fig. 1. ***Overview of the four different categories of context-aware and class-based broadcasting to support a variety of different application domains in vehicular networks.***

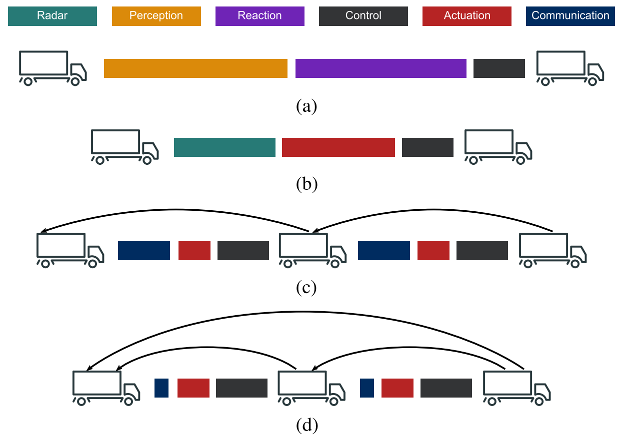

Fig. 2. ***Comparison of vehicle following approaches with their typical achievable performance. (a) Manual driving (mainly depending on perception and response times): minimum headway time 2 s, i.e., 50 m at 100 km/h. (b) Radar based ACC: minimum headway time 1 s, i.e., 28 m at 100 km/h. (c) Simple CACC (radar plus IVC): minimum headway time 0.6 s, i.e., 16 m at 100 km/h. (d) Advanced CACC (multiple IVC links): speed-independent vehicle gap, e.g., 5 m.***

III. PLATOONING OF CARS

Platooning, or cooperative automated driving, is an intelligent transportation system (ITS) application that groups vehicles together in road trains, or platoons [13], [36]. Vehicles in a platoon autonomously follow each other at a close distance, all driven by a common shared leader. The leader can be controlled by a professional driver, as envisioned by the SARTRE project [37], it can be a self-driving vehicle, or it can be remotely controlled (teleoperated [38]).

This application tackles multiple road transportation issues together. The first one is traffic congestion. The increase in the number of vehicles without the upgrade of the road infrastructure is leading to a complete congestion of urban streets and freeways. Increasing road capacity by building new streets in cities or adding new lanes to freeways might either be too expensive or simply unfeasible.

The solution thus lies behind a more efficient use of the existing infrastructure, which, in turn, means reducing the wasted intervehicle spacing due to safety distances. According to recommendations, the safety gap should be 2–4 s, which translates into an actual distance around 55–110 m for a cruising speed of 100 km/h [Fig. 2(a)]. This gives an idea of the wasted capacity on roads today.

Reducing intervehicle spacing can only be achieved with an automated driving system, as human drivers cannot handle short distances without compromising safety. One possible way is through sensor-based systems, such as the adaptive cruise control (ACC) [Fig. 2(b)], or brand-new self-driving cars. Although both seem to be promising, they would not actually improve the situation much, as their perception is somewhat limited for human beings. Sensor-based solutions work only in LOS conditions, i.e., they cannot see behind corners or past other vehicles. Moreover, and maybe more fundamentally, for system stability (and thus safety) reasons, these solutions must keep a safety distance which is comparable to the one kept by human drivers [12], resulting in no traffic improvement or, in some cases, even reducing the traffic flow [39].

The solution is thus through connected and cooperative vehicles. Sharing information through a wireless link solves the LOS problem, increasing the perception that a vehicle has of its surroundings. This permits the design of CACC systems [12], [40]–[43], which are at the core of the platooning application. A CACC is an advanced version of a standard ACC that exploits data received from other vehicles to improve the reactivity to any event, permitting to reduce intervehicle distance without compromising safety. As an example, the leader of a platoon can share its dynamics data so that all followers can replicate its actions in real time [Fig. 2(d)]. This permits to maintain speed-independent intervehicle gaps in the order of a few meters, as witnessed by the pioneering California PATH project [44] or in the European Project SARTRE [37]. Other proposed implementations require communication only between consecutive pairs of vehicles [40]. On the one hand, this avoids the necessity of a communication link to the leader but, on the other hand, the vehicles must use a time headway-based spacing, which is smaller than the ACC one, but results in a larger intervehicle spacing than leader-based solutions [Fig. 2(c)]. This is necessary because, if the control system only considers data received from the preceding vehicle, actions performed by the leader are only detected due to the physical propagation of vehicle dynamics, which is inherently slow. When the control system explicitly considers data sent by the leading vehicle, each platoon member can immediately exploit this information almost simultaneously, making it feasible to tighten the intervehicle spacing without reducing safety.

The second issue tackled by platooning is safety. Congested freeways cause the formation of traffic shock waves, which are high-density waves of slowly moving vehicles that travel backward with respect to driving direction. Shock waves can form spontaneously due to the amplification of small traffic perturbations that are normally absorbed in low-density conditions [45]. They pose a high safety risk as they cause unexpected emergency braking maneuvers that can lead to chain collisions. Platooning can improve safety as the CACC takes over control of the vehicle and, most importantly by making traffic flow smoother, thus reducing shock wave phenomena [39], [46].

Last but not least, by reducing traffic shock waves, platooning can reduce CO_2 emissions eliminating start-and-stop dynamics that consume more fuel than constant speed cruising. In addition, tailgating reduces aerody-

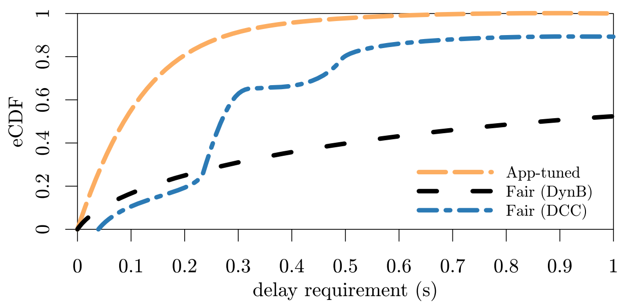

Fig. 3. ***Protocol delay performance (empirical cumulative density function of packets meeting the delay requirement) studying ETSI ITS-G5 DCC, DynB, as well as an app-tuned approach using platooning optimized transmit power and time slotting (figure inspired from [48]; for detailed results, see the original paper).***

namic drag, which can account for the 75% of the tractive force during highway cruising [47].

Platooning has clearly tight requirements on the wireless communication network. In particular, an update frequency in the order of 10 Hz is commonly assumed [40], although this can be relaxed, if very high communication reliability can be provided, to 5 Hz [48]. More recent work shows that this might even change depending on vehicle dynamics [49]. It is well known, however, that WLAN-based technologies such as IEEE 802.11p [7] suffer high packet loss ratio due to channel congestion, and in really dense scenarios they would simply be unable to meet CACC requirements. A detailed study in [48] shows that the current standard for vehicular networking in Europe, ETSI ITS-G5 DCC, is not able to guarantee such delay requirements (see Fig. 3). Other approaches such as dynamic beaconing (DynB) fail as well, only achieving a latency of 200 ms in less than 20% of the cases. When trying all tricks known in the field of wireless communications including optimization of the transmit power and assigning time slots for communications, the situation improves but still the delay requirement is not met in all cases as the App-tuned curve in Fig. 3 shows.

We find studies that address such limitations by exploiting the natural structure of platoons. As an example, we can reduce intraplatoon channel contention by synchronizing communication between platoon members [50] and interplatoon interference by adapting transmit power control [48]. In addition to such mechanisms, we can increase intraplatoon reliability by implementing distributed reliable broadcast protocols through retransmission schemes [51].

Although promising, such approaches only focus on the network without looking at the actual requirements, which might be time varying [49]. The solution, as well as the challenge, can be found in the Tactile Internet concepts, where the design of the system jointly considering the application, the control system, and the communication mean represents a nonmarginal step forward.

In addition, the Tactile Internet finds application in the remote control of the leading vehicle. Such application requires real-time data transfer between the vehicle and the control center, but the nature of the link is different with respect to the CACC use case. The CACC requires a localized broadcast link that should periodically transfer small amounts of data, such as acceleration, speed, and position. However, the network is self-organizing, so there is the possibility of channel congestion. The remote control link, instead, is a unicast connection through an infrastructure-based network, which must continuously transfer control commands and visual feedback between the vehicle and the operator. The amount of data to be transferred is higher compared to what is required by a CACC, especially for the visual feedback. On the other hand, in an infrastructure-based network, we have the possibility of preallocating the resources. Still, this is not something that can be achieved with a standard telecommunication network, so Tactile Internet concepts are definitely needed in this context.

IV. TACTILE-INTERNET-BASED SOLUTION SPACE

In the following, we investigate two possible approaches to address the lack of communication guarantees in CACC-based platooning solutions. The first approach is to rely on an integrated design paradigm for network protocols and the underlying vehicle control loop. The second approach is to use multiple heterogeneous communication technologies complementing each other. These approaches are orthogonal to one another, i.e., can be used in combination for future robust and safe platooning solutions.

A. Joint Network/Control Design

A promising method to realize cooperative driving is through a multidisciplinary approach. Early studies both in the control theory and in the networking areas did not consider limitations and problems outside their scopes. As an example, the CACC developed in the PATH project does not even consider communication impairments [44]. The CACC developed by Ploeg *et al.*, instead, models the wireless network with a delay, which does not capture all problems a wireless network can experience [40]. On the other hand, we find communication studies that try to maximize packet delivery without considering the real requirements of the control system [48].

Recently, we have witnessed a change in perspective, with the two communities joining forces to design the control system and the communication protocol together. One example is the work in [14], where Öncü *et al.* analyze the stability of a CACC in a control-theoretical framework, but consider a more realistic modeling of the network behavior with respect to the one assumed in [40]. In particular, the authors model network impairments as a constant delay together with a zero order hold (ZOH) that emulates the sampling effect. The work derives stability conditions of the system depending on time headway, transmission delay, and sampling time.

The work in [49] proposes an adaptive protocol named *"Jerk Beaconing."* The authors observe that the data requirements of the CACC depend on the dynamics of the vehicles. If the dynamics of a vehicle are constant, periodic broadcasting simply wastes resources, as other vehicles can predict the state by knowing the initial one and the amount of time elapsed since the generation of the initial state. Under this assumption, the work proposes an empirical function that computes the next packet sending time depending on how much the acceleration changed since the last sent update. The larger is the difference, the shorter the sending interval. In addition, the adaptive beaconing scheme is coupled with a reliable delivery protocol, which ensures the immediate retransmission of the packet in case of loss. The results shows that the approach not only reduces network resource utilization, but also that it is even safer than standard periodic beaconing, because data are sent at the right instant and due to the prediction mechanism. This approach, although empirical, is a proof of concept showing the importance of a joint design. A similar dynamics-based approach is present in the DCC algorithm of ETSI ITS-G5 [11] which, however, is not capable of meeting low latency requirements as shown in [48] due to the congestion caused by high-speed driving.

Dolk *et al.* [52] pursue a very similar concept, although in a control-theoretical framework. The authors oppose the idea of event-driven control to standard time-driven control, i.e., control information is sent in the network only when required to ensure system's stability. The idea is first mathematically formalized and then verified with a benchmark composed by three cars and an IEEE 802.11p radio. In their experiments, the adaptive scheme is compared to a static, 25-Hz beaconing, showing that the system achieves exactly the same performance but with less resource utilization. Differently from [49], however, no packet loss recovery is implemented.

We then find another joint network/control design which, differently from [49]and [52], does not adapt the message dissemination rate, but instead derives distance error bounds subject to packet losses and vehicle performance. Given a certain number of possible consecutive packet losses and the maximum vehicle dynamics in terms of jerk, the framework derives an upper bound on the distance error, which can then be applied as the actual intervehicle spacing. The simulative analysis shows that such bounds are always respected. In fact, as the experiments employ a prediction mechanism as in [49], the bounds are respected by a large margin.

These works clearly highlight the potential behind joint network/control design approaches. Expert domain knowledge is needed from both fields to eventually construct high-quality Tactile Internet solutions. We can conclude that it is of utmost importance to work in a multidisciplinary manner for the design of cooperative driving systems.

B. Heterogeneous Communication Technologies

An orthogonal approach is to improve communication behavior by relying on multiple communication technologies at the same time. This idea has become popular under the name heterogeneous networking with applications in 5G networks for further improving data rates but also in the Tactile Internet era to reduce latencies and to improve communication reliability in general [53], [54].

In the field of vehicular networking, this concept has been identified as one of the most important research questions [55], [56]. Many approaches concentrate now on the complementarity of IEEE 802.11p and LTE [57]–[59]. Most cases actually look into clustering cars to reduce the overhead on the control plane and, therefore, improving data plane communication [60], [61].

In this section, we concentrate on yet another set of communication protocols, namely LOS techniques, that are of particular interest in the domain of cooperative driving and platooning to complement some of the already discussed deficiencies of IEEE 802.11p. The best known examples are millimeter-wave communication in the upper gigahertz band [62]–[64] as well as visible light communication (VLC) using the frequency bands beyond radio-frequency (RF) technologies [30], [65], [66]. Without loss of generality, we concentrate on VLC in the following but the concepts and ideas are applicable to mmWAVE communication and vehicular radar as well.

The first study on using a heterogeneous approach based on the combination of IEEE 802.11p and VLC has been presented in [67]. The paper addresses the main two problems of IEEE 802.11p-based platooning solutions: First, congestion on the wireless channel may lead to packet loss and, therefore, may require a substantial increase of the desired distance between following vehicles to ensure safety. Second, security concerns need to be considered, from jamming of the channel (which translates to packet loss) to malicious attacks. Both problems are addressed by integrating VLC as a second communication channel. In fact, the following communication pattern was considered: Only the platoon leader uses IEEE 802.11p and communication between consecutive vehicles is realized through VLC. By using an 802.11p link, the leader reaches all platoon members simultaneously, which is fundamental for CACC systems that rely on a leader- and predecessor-following control topology [42], [44], [68]. The VLC link, in addition, can be used as a repropagation mean in case 802.11p leader beacons are lost. The impact of the delay introduced by the repropagation mechanism is still an open question. Each platoon leader is controlled by an ACC, while all the followers use the CACC controller described in [48]. This way, even multiple platoons on the same lane can be supported in realistic freeway environments.

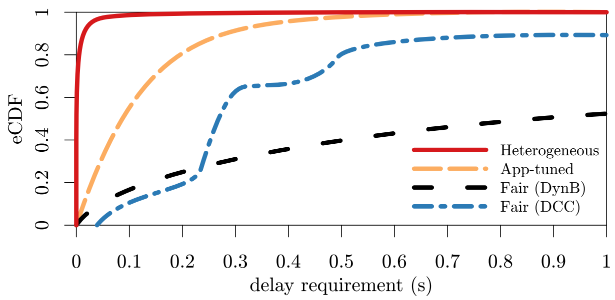

Fig. 4. ***Protocol delay performance as shown in Fig. 3 now adding a curve for the heterogeneous networking approach using IEEE 802.11p and VLC (for detailed results, see [67]).***

For this initial analysis, a simplified, purely stochastic, VLC channel and physical layer model was used. In particular, assume a maximum reception range of 25 m was considered as well as a decoding delay (i.e., processing time) to be distributed according to a truncated normal distribution (strictly positive) with a mean of 20 ms and a standard deviation of 1 ms. These values were tuned for a charge-coupled device-camera-based receiver with a rather fixed processing delay, which becomes negligible when switching to a photodiode-based receiver [29]. At this short distance, also the light radiation pattern has almost no impact, which must be considered for larger distances [34].

In order to test the combined IEEE 802.11p/VLC approach, a freeway scenario was used in a traffic jam situation as in [48]. In particular, a four-lane freeway was simulated with 160, 320, and 640 cars divided in platoons of 20 cars. As shown in Section III, particularly the dense scenario has been shown to fail (i.e., to miss the 200-ms delay requirements) using IEEE 802.11p only. The key reason was the high load on the network leading to congestion and eventually packet loss.

Fig. 4 shows the figure we discussed already in Section III. This time, a curve for the heterogeneous approach using IEEE 802.11p in combination with VLC has been added (cf. [67] for more details). As can be seen, the heterogeneous communication solution not only substantially outperforms all IEEE 802.11p-based solutions but even guarantees to meet the delay requirements in all cases.

Similar results can be achieved by combining IEEE 802.11p with other LOS technologies such as mmWAVE using automotive radar [64], [69].

C. Research Roadmap

In summary, Tactile Internet solutions can help making cooperative driving a reality from a technical point of view. From a research roadmap perspective, the following challenges need to be addressed on a fundamental level:

- ultralow latency and ultrahigh reliability—to allow remote control of cooperative driving maneuvers; this can be achieved by
- design of integrated network protocols—to enable closed-loop control algorithms in networked systems; and
- combination of complementary communication technologies such as short-range RF (e.g., IEEE 802.11p) and LOS solutions such as mmWAVE or VLC.

V. FURTHER RESEARCH CHALLENGES

Based on our investigation of communication concepts for supporting ultralow-latency and very-high-reliability applications in the automotive environment using platooning as an example, we discuss selected open research challenges in the following. We aim at guiding researchers that are new in the field or who are thinking about different angles to approach the problem. This list can by no measure be complete. Instead, we focus on three important aspects that also have been debated strongly in recent conferences.

A. Scalability and Dependability

From the communications perspective, cooperative driving will pose big challenges in the dependability and scalability of the networking system. The two topics are different, but intertwined, and neither of them received sufficient attention so far. The question of scalability has been raised already, but mainly in the form of channel congestion control, which is definitely a wrong perspective. Any safety-related communication, be it for cooperative driving or for any other application of the Tactile Internet, cannot wait for the congestion on the channel to subside before the information is sent. Indeed, the scalability issue must be tackled from the perspective of guaranteeing that enough resources are available to always support safety applications, i.e., from a resource allocation perspective. This entails not only a proper policy to guarantee that enough spectrum is allocated for cooperative driving, but also that within that spectrum the communication devices can follow the technological trend to improve the spectrum efficiency, e.g., with the adoption of multichannel/multiradio devices as well as massive multiuser–multiple-input–multiple-output (MU–MIMO) techniques. Needless to say, MU–MIMO technology has never been explored in conjunction with multicast/broadcast communications; and in the vehicular environment, it has hardly even been mentioned. Moreover, scalability in cooperative driving means finding proper ways of ensuring the “graceful degradation” of the system toward autonomous and/or human driving (cf. Section V-C), when, whatever the reason, the communications system cannot sustain anymore the globally entangled cooperative driving maneuvers.

This is where scalability intertwines with dependability. Clearly nobody can even consider the idea that cooperative, autonomous vehicles fail when they are most needed, i.e., when safety is at stake. This is why we refer to dependability and not reliability: A system that is reliable

99.999% of the time, but fails when human safety is at stake is not only useless, but indeed dangerous. To guarantee full dependability, communications for the mobile Tactile Internet must be based on properly coordinated and physically different communication means. Several channels are needed, and they must be as uncorrelated to each other as possible, so that dependability is achieved. For instance, in the realm of cooperative driving, we can imagine that not only local short-range radio techniques are used in parallel with cellular networks, but also communication channels built on VLC as well as mmWAVE communications techniques. This is a sound assumption given the widespread use of LED lights as well as radar ranging devices measuring distance of vehicles in front, behind, and around.

Besides posing interesting problems and questions on resource organization and orchestration, the presence of several communications channels for dependability, if properly managed, also support scalability. Once several communication channels are available, the congestion or unavailability of one of them is just another event to be considered within the global management of safety and cooperation, for instance, by relaxing the performance requirements to improve the system resilience.

B. Security and Privacy

Security in cooperative driving is especially challenging as it is strictly related to safety. A system that is insecure leaves room for attacks, which could have serious consequences. Besides the public safety concerns, accidents during the initial rollout phase might negatively influence the public opinion, which already shows concerns about riding in self-driving cars [70].

Security in this context embraces different aspects, including system design and communication. All the devices involved in cooperative driving, including the vehicle itself, must be tamper-proof. From the vehicle perspective, cooperative cars will be equipped with actuators for electronic control purposes. Needless to say, gaining access to any of the in-car components can give an attacker the possibility of controlling the entire car. Here, however, we put our focus on security concerns regarding communication as a key feature of the Tactile Internet.

Tampering of the onboard unit (OBU) can lead to different possible attacks. First, it could be possible to attack the vehicle on which the tampered OBU is installed. The attacker could feed malicious data to the CACC, causing the vehicle to accelerate or decelerate at his/her own will [71]. To protect against such attacks, besides properly designing OBUs from a security perspective, a data-fusion layer should serve as an additional barrier against malicious data. Ideally, data fusion should take data from multiple sources, detect erroneous data, and discard it, potentially warning the system about the problem. The second type of attack exploits the radio for sending fake but authenticated messages. As CACC algorithms are not designed to cope with malicious network impairments, this may trick vehicles in the same platoon causing collisions [72], [73].

In both attack scenarios, it is data that should be made timely and reliable, as data are the means to cooperation. For this reason, we believe the research direction must not be vertical, aiming at making one particular communication technology able to support cooperative driving, but rather horizontal. Multiple technologies should be put together to realize parallel links between the vehicles, providing redundant communication (cf. Section V-A). Data can (and must) be fused and checked for consistency before being handed over to control algorithms.

In addition, we must change the way we design control algorithms to specifically take into account the effects of communication failures, e.g., due to a jamming attack. This provides safety margins that can be exploited for counteracting data losses. In particular, disaster recovery procedures need to be developed that are triggered by certain events. What should clearly be defined are such triggering conditions and the best actions to be taken to ensure passengers' safety; both of which are still open research problems. Again, relying on, for example, LOS communication technologies as discussed before, offers additional opportunities also for security—simply because it is very hard for an attacker to compromise VLC or mmWAVE links.

Strictly related to security is privacy. Some authors have discussed that privacy and security conflicts in this context. However, works like [74] already question the strong clash between privacy and safety, if not for else because vehicles on the road neither require, nor have today, strong anonymity. This said, research on the proper means to protect users' privacy in cooperative driving is far from concluded, and indeed the extremely low latency requirements of the Tactile Internet add challenges to privacy protection methodologies like the use of time-varying pseudonyms, group authentication, and so forth.

Once more the platooning applications is clarifying: How can the identity of vehicles forming a platoon be reasonably concealed while the control information is distributed in the platoon? Furthermore, should this information be cryptographically protected so that only vehicles involved in the platoon can receive it or not? Indeed, privacy and anonymity protection for road users is a very broad issue that involved technical issues, but also legal and societal questions and decisions: Far fetching, visionary, and interdisciplinary research is needed along this path.

C. Public Acceptance

One of the most critical questions when it comes to deploying any new technology is public acceptance. Indeed, there is no field where automation is as critically discussed and argued about as automotive and the ability to drive on your own account. Right now, we see many activities worldwide to enable automated driving not only from a technological point of view but most importantly from both social and legal ones. Regarding the social aspects, in-depth studies have been conducted to analyze the sociopsychological impacts of public acceptance [75]. Seemingly, there is a multitude of aspects that even depends on the cultural and historical developments of a specific country.

Furthermore, there is the very important problem of lacking correct self-assessment by many or even most people, particularly, when it comes to questions like who is a good driver. The well-known Dunning–Kruger effect [76] explains the cognitive bias, wherein persons of low ability suffer from illusory superiority when they mistakenly assess their cognitive ability as greater than it is. This has been confirmed in many empirical studies investigating public acceptance of automated driving [77]. The outcome is that a substantial group of people simply rejects the idea due to their (wrong) belief that they are able to handle problems better. Legal issues, on the other hand, have in part already been addressed successfully in many countries. First field trials are being conducted worldwide and automated driving has been legalized in many places.

These observations go hand in hand with findings that automated decision making is moving more into the focus of the public. In automated driving, cars have to make decisions that possibly affect (and threat) human lives, including the car owner's one. The frequently cited example of, when being in a very critical situation, whether the car should prefer the driver against pedestrians has been modeled in-depth by the MIT moral machine [78]. In a huge variety of situations, one can test his own decision preferences to see how complex automated decision making can get.

Getting back to cooperative driving, the situation gets even worse. Here, only automated cars can successfully interact to, e.g., form a platoon and drive safely with a gap of just a few meters between each car. Human drivers will never be able to handle the required short reaction (and perception) times. On the other hand, there will be legacy cars driven by human drivers. Together with semiautomated and fully automated cars, they form what is now called a CPSS [5]. The impact of communication technologies on such CPSSs is not understood completely and there is a strong need to reiterate on accepted solutions and their application on such complex systems where human drivers interact with automated cars in a closed-loop fashion.

D. Research Roadmap

In summary, Tactile Internet solutions need to be enhanced to also cover nonfunctional aspects substantially affecting cooperative driving maneuvers. From a research roadmap perspective, the following challenges need to be addressed on a fundamental level:

- scalability is at the core of many of the research questions discussed and often solutions work pretty well as long as only a limited number of systems participate in the network;
- security solutions have been defined in standardized protocol stacks but often either limit scalability or they introduce privacy concerns;
- human interaction affects technical solutions either due to acceptance problems or, if the human is part of the system, due to limited reaction times or misleading self-assessment of own capabilities.

VI. CONCLUSION

We studied the need of novel communication paradigms supporting the emerging field of cooperative driving. Particularly, when it comes to safety-critical applications such as CACC and platooning, where safety gaps of less than 5 m need to be controlled not only using local sensors but most importantly input obtained from neighboring cars via wireless communications, state-of-the-art solutions do not provide the required degree of reliability and the necessary guarantees on low latencies. The Tactile Internet initiative has been formed having exactly these objectives in mind. We have shown how such concepts, in particular the use of integrated network/control design as well as the use of orthogonal heterogeneous communication technologies, help overcoming some of these challenges. In conclusion, it can be said that some first steps have been done successfully in applying Tactile Internet solutions to cooperative driving, but there is still a long way to go for enabling large scale deployment while meeting all the safety requirements. □

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