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Standards for vehicular communication—from IEEE 802.11p to 5G

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Standardization for wireless vehicular communication ensures, as in other domains, interoperability, supports regulations and legislation, and creates larger markets. For the initial deployment of vehicular communication, consistent sets of standards have been created, commonly named C-ITS in Europe and DSRC in the U.S., both relying on the WiFi standard IEEE 802.11. These initial standard sets specify vehicle-to-vehicle and vehicle-to-infrastructure communication and enable applications primarily for driver information and warnings. The article provides an overview of the key C-ITS and DSRC protocols from a standardization perspective. The article analyzes automated driving as the potential new application domain for vehicular communication, discusses its requirements on communication, and derives potential directions for future releases of the vehicular communication standards.

Keywords: vehicular communication; safety; traffic efficiency; standards; automated driving; 5G

Standards für Fahrzeugkommunikation – von IEEE 802.11p zu 5G.

Standardisierung für drahtlose Fahrzeugkommunikation ermöglicht, wie auf anderen Gebieten, Interoperabilität, unterstützt Regulierung und Gesetzgebung und schafft größere Märkte. Für die bevorstehende Einführung von Fahrzeugkommunikation wurden konsistente Standards entwickelt, und zwar für C-ITS in Europa und DSRC in den USA; beide Systeme basieren auf dem WLAN-Standard IEEE 802.11. Diese initialen Standards spezifizieren Fahrzeug-zu-Fahrzeug- und Fahrzeug-zu-Infrastruktur-Kommunikation und unterstützen hauptsächlich Anwendungen zur Fahrerinformation und -warnung. Dieser Artikel gibt einen Überblick über wichtige Kommunikationsprotokolle in C-ITS und DSRC aus einer Standardisierungsperspektive. Der Artikel analysiert automatisiertes Fahren als eine wichtige neue Anwendungsdomäne für Fahrzeugkommunikation, diskutiert die Anwendungsanforderungen an Kommunikation und leitet potentielle Richtungen für zukünftige Releases von Standards für Fahrzeugkommunikation ab.

Schlüsselwörter: Fahrzeugkommunikation; Sicherheit; Verkehrseffizienz; Standards; automatisiertes Fahren; 5G

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1. Introduction

Intelligent Transport Systems (ITS) comprise emerging information and communication technologies to improve the transport of people and goods. ITS covers a wide range of applications for any type of transport. In recent years, major advances have been made in the area of WiFi connected vehicles. A specific WiFi mode operating in the 5.9 GHz frequency band, formerly known as the 'p' amendment of the IEEE 802.11 standard, enables ad hoc communication and the direct exchange of information among vehicles in their vicinity, including the communication between vehicles and the roadside infrastructure. This approach is commonly referred to as vehicle-to-any (V2X) communication. Compared to cellular networks, WiFi-based V2X communication does not offer a pre-installed infrastructure and (almost) full spatial coverage, but its capabilities for direct communication among nodes with short communication latency makes it a strong candidate for vehicle safety and traffic efficiency applications. Typical examples for these applications are emergency electronic brake light, road hazard warning, and green light optimal speed advisory.

WiFi-based V2X communication technology has reached a mature stage and a basic V2X system is expected to be deployed in the next few years. The initial set of applications—raising the driver awareness, disseminate warnings and provide real-time traffic information—are well aligned with the capabilities of the technology. The basic system still leaves opportunities for enhancements. For example, with a growing rate of V2X-equipped vehicles the single transceiver, single channel V2X system will likely be extended to a multi-transceiver, multi-channel system. In addition, new application domains, in particular automated driving, put new functional requirements on the communication system. These functional requirements are associated with higher performance demands for data rate and patterns, communication reliability, and latency. Potentially, the higher requirements can be met by improvements of the WiFi-based V2X communication system. As an alternative, the next generation of cellular networks, 5G, targets at very high data rates, massive number of devices, very low latency and very high reliability. 5G research and development efforts are underway that consider requirements for automated driving and other vehicular applications.

An essential requirement for the deployment of V2X communication systems are international standards, which provide specifications to ensure interconnection among V2X (sub-)systems and components as well as interoperability of implementations from different vendors. In addition, standards also serve a variety of other purposes: Open standards create trust of customers in products and services, create larger markets than proprietary systems, lower development costs, and increase competition among vendors. How-

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ever, V2X standardization also faces a number of challenges. From the technical perspective, V2X standards comprise a large number of base and test specifications from different domains ranging from radio and protocols to security and applications. The large number implies a high complexity with a risk of incompleteness and inconsistency. The development of standards in releases bears the challenge of forward- and backward-compatibility among releases, in particular when new features and application classes are added. From the non-technical perspective, V2X standardization is addressed by several standardization development organizations (SDOs), which have produced partially overlapping specifications. The combination of standards from different SDOs is challenging, a harmonization of standards time- and resource-consuming. Finally, standards not necessarily incorporate latest research and state-of-the-art technology (such as eCall), and may also become a barrier for innovations; in particular small innovative companies may have difficulties to include their cutting-edge technologies.

The present article provides an overview of standards for V2X technologies and potential future directions. The remaining sections of the article are organized as follows: Sect. 2 presents the standardization landscape analyzing key organizations and the development status. Sections 3 and 4 provide an overview of release 1 standards for V2X communication in Europe and in the U.S. Section 5 describes trends and directions for future releases. Section 6 concludes the article.

2. Standardization landscape for vehicular communication

ITS standardization is foremost a matter of official SDOs, where V2X communication is only one aspect of their standardization efforts, though currently the most dynamic area. First standardization efforts in Europe date back to the 1990ies, where specifications for Traffic Message Channel (TMC)[1] and Electronic Fee Collection (EFC)[2] were developed in the context of Real-Time Traffic Information (RTTI). Standardization of WiFi-based V2X communication started with the allocation of the 5.9 GHz frequency band in the U.S., which was granted in 2002. Historically, standardization in the U.S. and Europe has developed in parallel, mainly because the activities were supported by different research and development programs and promoted by different stakeholders; finally they led to different sets of standards. These two approaches will be referred to as Dedicated Short Range Communication (DSCR) in the U.S. [1] and C-ITS in Europe [2] throughout this article. Still, the technical approaches of C-ITS in Europe and DSCR in the U.S. have many similarities, whereas the V2X communication systems in other regions are different, such as the ITS communication system in Japan operating at 700 MHz. At ISO, standardization activities have created the CALM[3] family of standards, a system that incorporates various communication technologies and transmission modes into a single system. Also, ITU and 3GPP have initiated first standardization studies. This article focuses on the standardization of C-ITS in Europe and DSRC in the U.S. as they are the most relevant for the planned deployment in the next years.

In Europe, the major SDOs active in the C-ITS area are ETSI and CEN with their technical committees (TCs) ITS and 278, respectively. CEN cooperates closely with ISO, i.e. TC 204 and produces joint specifications. Supported by a mandate of the European commission, ETSI and CEN have created a consistent set of standards for a minimal deployment, which is taken as basis for European deployment. For this set, ETSI has focused on specifications for the communication system and vehicle-to-vehicle applications; CEN has mainly produced standards for vehicle-to-infrastructure applications. In order to ensure that the standards do not conflict with national standardization activities in Europe, ETSI and CEN have produced European Norm (EN) that were approved by the National Standardization Organizations (NSOs) of the EU members and associated states, and are made legally binding. This has been achieved by a mandate issued by the European Commission for the development of a minimum and consistent set of standards for C-ITS, completed in 2013. The European standardization efforts are accompanied by activities of the *Car-2-Car Communication Consortium* (*C2C-CC*) [3], an industry consortium of automobile manufacturers, suppliers, and research organizations, *ERTICO*, an European organization of public and private stakeholders, and ETSI CTI, ETSI's center for testing and interoperability. The CC-CC has developed a profile of the European C-ITS release 1 that restricts the large set of standards and complements missing specifications. In 2013, automobile manufacturers in C2C-CC signed an agreement for the introduction of the system. Deployment plans are being developed in the *Amsterdam Group* [4], a strategic alliance of stakeholders of C-ITS in Europe, with *CEDR–ASECAP–POLIS*, representing stakeholders for the ITS infrastructure on highways, cities and traffic management, and the *C2C-CC*. Pilot deployment projects support the system introductions. For example, a trilateral C-ITS corridor that interconnects Vienna–Frankfurt–Rotterdam will be equipped with roadwork protection systems for highways until 2018 [5].

In the U.S., relevant SDOs are IEEE[4] and SAE,[5] more specifically the 802.11 Wireless LAN and the 1609 DSCR working groups from IEEE, and the DSRC technical committee from SAE. Relying on the DSRC spectrum allocation, IEEE has developed the IEEE 1609 standard family that specifies protocols on top of the IEEE 802.11 PHY and MAC. This combination of IEEE 802.11 and 1609 standards is widely known as WAVE—Wireless Access for Vehicular Environment. Above the protocol stack, V2X message sets and related performance requirements are specified by SAE. Altogether, the WAVE standards, message sets and performance requirements make up a consistent set of standards ready for deployment. Unlike in Europe, where deployment is industry-driven and voluntarily, a regulatory decision is expected in the U.S. This rulemaking process has been initiated to make DSRC mandatory, indicating a deployment at the beginning of 2020.

3. Dedicated Short Range Communication (DSCR) standards in U.S.

DSRC relies on the widely deployed WLAN standard defined in IEEE 802.11-2012 [6], which defines the physical transmission (PHY) and medium access control (MAC) (see Fig. 1 that shows the overall DSCR protocol stack). PHY and MAC are derived from the former IEEE 802.11a standard, and adapted to the requirements for V2X communication. Like IEEE 802.11a, DSRC operates in the 5 GHz frequency band (U-NII band), but shifted from the regular WiFi channels to the dedicated DSRC channels. These channels range from 5.825 GHz to 5.925 GHz, commonly referred as the "5.9 GHz band". The spectrum is subdivided into 10 MHz channels. DSRC also uses Orthogonal Frequency Division Multiplexing (OFDM), a state-of-the-art and widely used multi-carrier transmission scheme

[1] TMC delivers traffic and travel information via the FM broadcast radio.

[2] EFC is another name for road user charging.

[3] Communications Access for Land Mobiles.

[4] Institute of Electrical and Electronics Engineers.

[5] Society of Automotive Engineers.

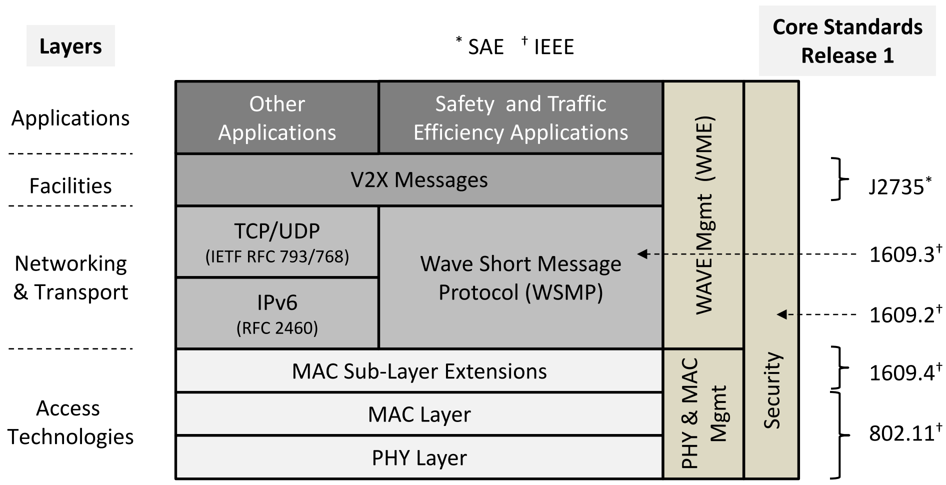

Fig. 1. Protocol stack and related core standards for DSRC in the U.S.

that is robust against interference and fading, and re-uses the same preamble and pilot design for synchronization and channel estimation. Compared to the common usage in WiFi, OFDM operates with "half clock", which reduces the commonly used 20 MHz channel spacing to 10 MHz and doubles the time parameters, in particular the OFDM symbol duration with the cyclic prefix. These changes attribute to the characteristics of the wireless channel in vehicular environments as it can cope with inter-carrier interference caused by Doppler spread due to fast moving vehicles [7].

The most relevant functional change for V2X communication is related to network formation: In general, IEEE 802.11 defines the Basic Service Set (BSS), which represents group of stations in the terminology of the standard. A BSS enables various network topologies, such as networks with an access point or mesh networks. IEEE 802.11 devices need to be a member of a BSS in order to exchange messages. Joining a BSS implies management procedures, such as channel scanning, association, etc. For V2X communication, vehicles in communication range need be able to exchange data immediately, without prior exchange of control information. For this reason, a new mode *outside the context of a BSS* (*OCB*) has been defined, which disables all control procedures common in BSS. Moreover, when a station supports several modes, it can be configured to a single mode at a time only, i.e. OCB or infrastructure mode. For medium access, stations in OCB mode use the enhanced distributed channel access (EDCA). EDCA is contention-based and applies the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). With CSMA/CA, a device listens to the channel before starting its own transmission; if the channel is occupied, the station delays its own transmission by a random duration of time. Stations differentiate data, assign the data to access categories (ACs), and handle the data from different access categories with other CSMA/CA-related parameters, which effectively allows for data traffic prioritization.

The Internet protocol (IP) is the default networking protocol for many today's networks. In combination with the transport protocols UDP and TCP, it is therefore also employed in DSRC. However, many V2X applications apply direct communication among vehicles and between vehicles and roadside units. For this purpose, the IEEE 1609 series of standards has been developed.

The Wave Short Message Protocol (WSMP) defined in IEEE 1609.3 is at the core of the protocol stack—a single hop network protocol with minimum header of few bytes. WSMP provides also the multiplexing of messages to upper layer protocol entities based on service IDs, hence fulfills the role of the transport protocol. In order to utilize the multiple wireless channels allocated in the 5.9 GHz frequency band, the IEEE 1609.4 standard defines a management extension to the MAC for multi-channel operation. It allows a DSRC system with one or several wireless transceivers to efficiently switch among the channel. This is achieved by separation of channels into control channels (CCH) and service channels (SCH). A service provider broadcasts service advertisement messages, which carries the channel number and other information. The receiver of such a message can tune its transceiver to a SSH. One of the channel switching modes defines a scheme with a single transceiver, where the time is divided into sync periods composed of CCH and SCH interval. The transceiver switches between CCH and SCH at the interval boundaries.

Security is defined in the IEEE 1609.2 standard and provides authentication and optional encryption of DSRC messages based on digital signatures and certificates. The authentication scheme also implies a security and a public key infrastructure, i.e. certificate authority (CA) and PKI, and policies for certificate validity, certificate encryption, and certificate revocation. In order to protect the privacy of drivers, certificates do not contain information about the driver, though the CA may link the certificate to a driver's identity. Furthermore, a vehicle uses a certificate only for a limited time and changes it frequently to make tracking more difficult.

At the facilities layer, the SAE standard J2735 defines syntax and semantics of V2X messages. Among the various defined message formats, the Basic Safety Message (BSM) is the most relevant. The BSM conveys core state information about the sending vehicle, including position, dynamics, status, and size. While the BSM is designed for compactness and efficiency, additional data elements and frames can extend it. These add-ons can be optionally included in a subset of the messages, e.g. every 2nd message. The BSM is a periodic message sent at a rate of 10 Hz maximum. A message rate algorithm [8] can reduce the BSM rate to keep the load on the wireless channel below a critical level. Other message tyes are related to communication between vehicles and the infrastructure, and are being harmonized with the European variants (see next section).

4. C-ITS standards in Europe

The parallel development of V2X communication has led to a different protocol stack in the U.S. and Europe. This section presents the

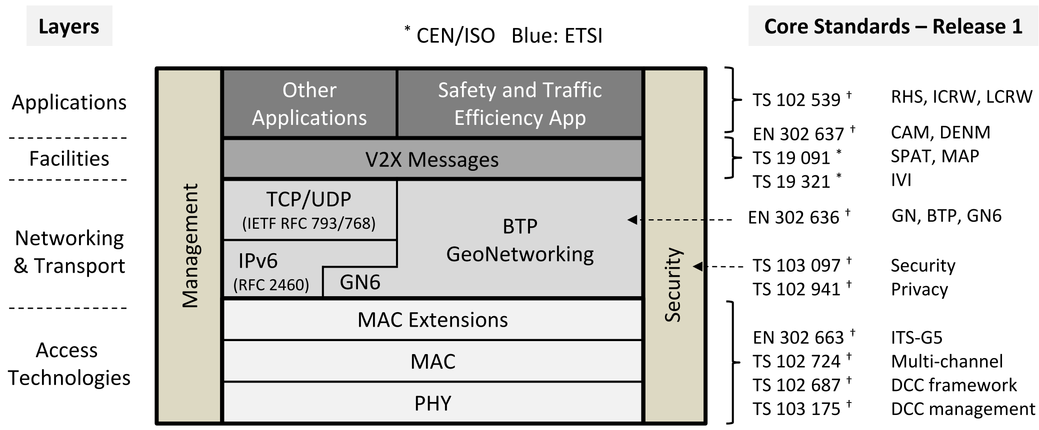

Fig. 2. Protocol stack and related core standards for C-ITS in Europe

C-ITS standards in Europe in comparison to the DSRC standards. Figure 2 shows the overall protocol stack and the corresponding core standard, keeping the same structure of horizontal layers for access technologies, networking & transport, V2X messages, applications, and vertical management and security entities as in Fig. 1.

The IEEE 802.11p equivalent in the C-ITS stack covering PHY and MAC is termed ITS-G5; the last two letters indicate that it operates in the 5 GHz frequency band. Like DSRC, it operates in the 5.9 GHz band, whereas the European spectrum allocation is sub-divided into part A to D. ITS-G5A with 30 MHz is the primary frequency band that is dedicated for safety and traffic efficiency applications, ITS-G5B has 20 MHz for non-safety application, and ITS-G5C is shared with the RLAN band. A specific requirement in Europe is also that the ITS-G5 spectrum must limit interference to the 5.8 GHz EFC system. However, the key technology features of IEEE-802.11 for DSCR and ITS-G5 are the same: At the PHY layer, it applies OFDM with the same parameter set, i.e. "half clocked" compared to IEEE 802.11a, but an adapted spectrum masks. At the MAC layer, ITS-G5 also employs EDCA with CSMA/CA and access categories allow for data traffic prioritization.

Standards for networking & transport and facilities also rely on the IP protocol for non-safety applications, but a major difference is at the protocols: While the usage of TCP/UDP and IP version 6 is similar, C-ITS specifies an ad hoc routing protocol for multi-hop communication, termed GeoNetworking and specified in the ETSI EN 302 636 standard series. Key feature of this protocol is the usage of geographical coordinates for addressing and forwarding. Its usage for addressing facilitates that all vehicles that are located in a geographical area can become the destination of a packet. While this is similar to broadcasting a packet to all neighbor vehicles, the geographical addressing makes the packet delivery independent from the communication range of a single wireless hop (which can vary from several 10 meters in unfortunate situations up to 1 km under line-of-sight conditions sometimes found on motorways). Also, the geographical coordinates are used to forward packets locally based on the vehicles' knowledge of its own position and the neighbor positions, and therefore enabling efficient multi-hop routing at low protocol overhead for establishment and maintenance of network routes in an environment with frequent topology changes. IPv6 packets can also be transmitted over GeoNetworking, for which the adaptation sub-layer GN6 (IPv6 over GeoNetworking) has been designed and standardized. Compared to the WSMP in the DSRC protocol stack, GeoNetworking is optimized for multi-hop communication with geo-addressing, which provides more technical features in application support, but comes with an increased protocol complexity and overhead.

Standards at the facilities layer define application-related functionality; most relevant are the V2X messages: Foremost, the Co-operative Awareness Message (CAM) (ETSI EN 302 637-2) [9] periodically conveys critical vehicle state information in support of safety and traffic efficiency application, with which receiving vehicles can track other vehicles' positions and movement. It can be seen as an equivalent to the BSM in the DSRC protocol stack. In addition, the Distributed Environmental Notification Message (DENM) (ETSI EN 302 637-3) [10] disseminates safety information in a geographical region. Unlike the CAM, which is periodically sent by every vehicle, the DENM transmission needs to be triggered by an application.

For vehicle-to-infrastructure communication, several services are defined that inform road users from the infrastructure side, control roadside infrastructure for priority access and preemption, and provide information from the vehicles to the infrastructure (see Table 1). These services define dedicated messages, namely the Signal Phase & Timing (SPAT) message for IIS, the MAP message for TPS, and the In-Vehicle Information (IVI). In the signal control service message are bi-directionally exchanged, i.e. it uses Signal Request (SR) and Signal Status (SS) messages. Finally, DENM and CAM are re-used for infrastructure-related services (INS and IAS).

Similar to the DSRC standards, C-ITS applications are not standardized directly. Instead minimum functional and performance requirements for three groups of applications are defined: *Road hazard signaling* (*RHS*) includes use cases such as emergency vehicle approaching, hazardous location and emergency electronic brake lights. *Intersection collision risk warning* (*ICRW*) and *longitudinal collision risk warning* (*LCRW*) refer to potential vehicle collisions at intersections and rear-end/head-on collisions.

5. Directions for vehicular communication standardization

5.1 New applications and use cases

V2X communication enables a wide range of applications. For the release 1 of standards, ETSI has categorized them into four groups, i.e. active road safety, cooperative traffic efficiency, co-operative local services, and global Internet services (see Table 2). A subset of use cases is considered for initial deployment, in Europe also referred to "Day 1 applications" in the Amsterdam group [15] and similar use cases for collision avoidance applications in the U.S. Among the application classes of release 1, active road safety has the most stringent communication requirements. Still, these requirements can be

Table 1. Overview of infrastructure services based on V2X communication (Source: ETSI TS 103 301)

Service name		Description
IIS	Intersection information service	Provides dynamic information about status of an intersection, such as traffic light state, residual time until traffic light changes, right of way for allowed maneuvers, public transport prioritization
TPS	Topology service	Offers static topology information for intersection or road segment, and paths for pedestrian crossings, for vehicles, public transportation
IVI	In-vehicle information service	Gives mandatory and advisory road signage information inside the vehicle, including static, variable and virtual signs; examples: such as contextual speeds and road works warnings.
SCS	Signal control service	Controls traffic lights for prioritization of public transport and preemption of public safety vehicles
INS	Infrastructure notification service	Informs vehicles and pedestrians about traffic situation, hazards, road works warnings, and other events
IAS	Infrastructure awareness service	Informs vehicles about existence of infrastructure (e.g., for interference management near tolling zones); estimation of traffic situation and flow based on messages from vehicles in vicinity

Table 2. Applications and selected use cases for Release 1 (Source: ETSI TR 102 638)

Applications Class	Application	Typical use cases
Active road safety	Driving assistance—Co-operative awareness	Emergency vehicle warning Intersection collision warning
	Driving assistance—Road Hazard Warning	Emergency electronic brake lights Wrong way driving warning Roadwork warning
Cooperative traffic efficiency	Speed management	Regulatory/contextual speed limits notification Traffic light optimal speed advisory
	Co-operative navigation	Traffic information and recommended itinerary In-vehicle signage
Co-operative local services	Location based services	Point of Interest notification Automatic access control and parking management
Global Internet services	Communities services	Insurance and financial services Fleet management
	Life cycle management	Vehicle software/data provisioning and update Vehicle and RSU data calibration.

regarded as relaxed, since all use cases target at the information of the driver or at increasing the driver's awareness. In all these use cases it is assumed that the duration of time for the driver to react is at most in the range of one second. The applications are also tolerant to packet loss, considering that messages are repeated by the originating vehicle or the same information is redundantly sent by different vehicles.

Beyond the release 1 applications, automated driving has received great attention in industry and academia as a major technology evolution of vehicles. Automated driving does not necessarily mean that the vehicle becomes human-driverless; instead different levels of automation can be distinguished. The definition from SAE[6] foresees six levels [11]. As illustrated in Fig. 3, the human driver still needs to monitor the environment up to level 2: It is assisted in some of the driving tasks (level 1) or the automated driving system executes some driving tasks, such as steering, acceleration/deceleration (level 2). In fact, to achieve automation levels 1 and 2, the use cases of V2X communication in release 1 play an important role. For higher automation levels, two basic use cases can be considered:

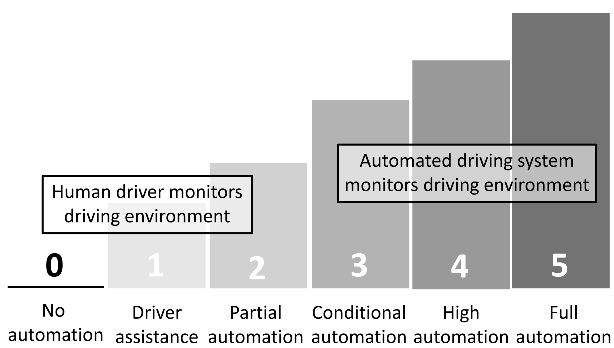

Fig. 3. Levels of automated driving as defined in SAE 3016 [11]

- *Dissemination of sensor data:* In the release 1 based V2X system, the exchanged information is highly aggregated. For example, the messages carry status information of the vehicle (e.g., speed,

[6]Similar definitions from the German Federal Highway Research Institute (BASt) and the U.S. National Highway Traffic Safety Administration (NHTSA) exist.

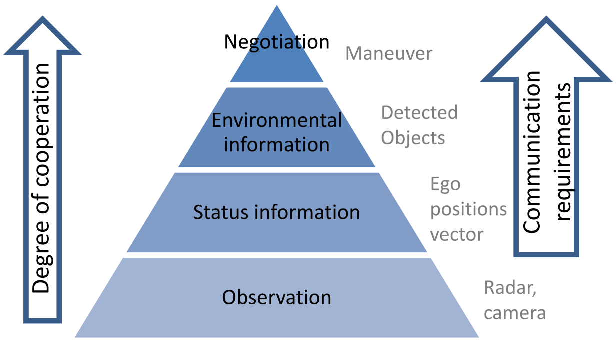

Fig. 4. Degree of vehicle cooperation

heading, etc.), topology and status data of an intersection/road segment, or coarse event-related data (e.g., traffic jam, location, etc.). The transmission of less aggregated sensor data or even raw sensor data enables an accurate fusion of local and remote sensor data, considerably increases the vehicle's range of perception considerably and extends the time horizon for situation prediction and trajectory planning in high automation levels.

- *Cooperative maneuvering:* An automated vehicle's control system need to add a safety margin into its planned trajectory, since it is uncertain how neighboring vehicles will behave. If vehicles would share their planned trajectories, or even negotiate among each other, the uncertainty is reduced and the safety margin could be minimized. Examples are automated lane change, overtaking, and ramp-on/ramp-off maneuvers on motorways. The synchronization of maneuvers may also lead to convoys of vehicles that share common mobility patterns, including loosely coupled formation without centralized control (also referred to as C-ACC[7]).

These use cases have the potential to unlock of a new domain of applications for driver assistance, vulnerable road user detection, or even tele-operated driving (e.g., for handicapped people). They are also regarded as a key functionality for higher level of vehicle automation (level 3–5 in the SAE J3016 categories). The functional requirements on the communication system grow with the degree of cooperation (Fig. 4), likewise the performance requirements will do. However, it is an open question to what extent the IEEE 802.11p/ITS-G5-based system is capable to meet these requirements.

5.2 Communication technologies

The IEEE 802.11p/ITS-G5 based V2X communication system has many favorable features that make it appropriate for road safety and traffic efficiency applications. It works fully distributed and hence does not require a coordinating network infrastructure. Data are exchanged directly among neighboring vehicles at a very small delay compared to an indirect transmission via an infrastructure. Network management is reduced to an absolute minimum, which enables an immediate exchange of data among vehicles without bulky signaling procedures. Multi-hop communication, as in the case of the European C-ITS, increases the limited communication range and enables to information dissemination in geographical areas. The V2X technology is commonly regarded as mature and appears therefore as the appropriate communication technology for the release 1 applications and use cases.

In general, the IEEE 802.11p/ITS-G5 based V2X communication system represents a compromise between availability of the technology and low complexity on the one side and state-of-the art communication technologies on the other side. The synchronization and channel estimation approach in IEEE 802.11 has originally been designed for stationary indoor reception and is sub-optimal for highly time-variant radio channels that are doubly dispersive in time and frequency. Also, the system does not use per-link rate adaptation via modulation, channel coding and power adjustment, nor advanced error control techniques for unicast, such as hybrid ARQ.[8] The spectral efficiency of this system is therefore considerably lower than a system with state-of-the-art solutions, such as turbo-coding and MIMO.[9] Furthermore, the V2X communication system relies on an un-coordinated channel access strategy (EDCA with CSMA/CA). With an increasing number of transmitters, the probability of data packet collision grows. In "hidden node" scenarios, the access strategy cannot even detect the presence of a transmission and the communication reliability further diminishes. The distributed approach precludes a coordinated assignment of transmission resources and interference management. To cope with data congestion on the wireless channels, additional protocol mechanisms maintain network stability and fair resource allocation, but at the same time, lead to a considerably higher end-to-end delay at the application despite the low latency offered by the physical transmission.

For future developments of IEEE 802.11p/ITS-G5 based systems, it is expected that fundamental transmission scheme at PHY and MAC layers will not change. This means that the sub-optimal performance at the lower protocol layers will remain. Some of the issues can be mitigated either by implementation-specific, IEEE 802.11-compliant improvements at PHY and MAC layers, or at the upper protocol layers, such as networking and facilities layers. In the latter case, smarter algorithms for information dissemination have the potential to improve the network performance and, at the same time, to maximize the safety benefit. Moreover, the current V2X system in release 1 is regarded as a basic system, indicating that it has a reduced set of functionality. This basic system will be implemented with a single transceiver, which is always tuned to a single wireless channel, i.e. the control channel. An extended system will likely use multiple transceivers in parallel and exploit the full V2x spectrum of multiple wireless channels. It is worth noting that so far, the release 1 of standards does not specify a complete and consistent set of performance requirements that implementations need to fulfill, such as the number of messages a vehicle need to handle at a minimum. While this activity has been started, its completion is required for future deployment.

Cellular networks, e.g. based on the 3GPP LTE standards, provide almost full radio coverage. Compared to IEEE 802.11p/ITS-G5, cellular base stations coordinate transmissions, such that collisions are avoided and interference minimized. Therefore, the system is able to guarantee data rate or delay to different applications. However, LTE has been primarily optimized for high data rate and its usage for V2X communication has several limitations: In order to communicate, a vehicle must always be synchronized and registered with the cellular network. This implies that communication is not possible out-of-coverage, such as in tunnels. In order to transmit a frame, a vehicle needs to request transmission resources (in terms of time slots and frequency sub-carriers) and the base station to schedule the transmission. Additionally to the implied signaling overhead, the data packet always traverses the cellular infrastructure, which results in longer latency compared to direct transmission.

[7] Cooperative Advanced Cruise Control or Cooperative ACC.

[8] Automatic Repeat reQuest.

[9] Multiple Input-Multiple Output.

Recently, a new feature known as Proximity Service (ProSe) or Device-to-Device (D2D) communication has been introduced into the 3GPP standards [12]. ProSe allows devices in communication range to discover their presence and to exchange data directly without sending the data via the cellular network infrastructure. ProSe defines "sidelink" communication, in contrast to the conventional up- and downlink in cellular networks. Sidelink data use a subset of the uplink time-frequency resources and the same transmission scheme as the LTE uplink transmissions, i.e. SC-FDMA.[10] When in coverage, devices use a scheduled mode for transmission, where the base station assigns the resources. Out of coverage, the device is in autonomous mode and selects the resources from a pre-configured resource pool. Originally, ProSe has been developed for scenarios with low mobility and point-to-multipoint communication, in particular public safety and consumer applications (e.g. social networking); and did not consider specific requirements for latency and reliability. In order to be used for automotive use cases, ProSe need to be enhanced with respect to functionality and performance.

5G, the next generation of cellular communication systems under development, is expected to meet the demands of various use cases that go far beyond distribution of voice, video and web data. 5G promises to be a single, common system that converges human-type communication with machine-type communication for various domains, such as industrial automation, robotics and tele-presence, transport & logistics, and others. 5G targets at significant increased performance in terms of more throughput, higher reliability and shorter latency, combined with support for a massive number of devices [13]. Even though not all of the extreme performance requirements need to be fulfilled at the same time, a new radio interface is being considered that provides the flexibility to be dynamically reconfigured for different scenarios and works in current frequency bands of cellular networks and new spectrum up to the millimeter wave range. The 5G research and development activities target at a time horizon of 2020. In this process, automotive requirements are being increasingly considered [14]. It is important to note that the integration of multiple radio access technologies (RAT) into the cellular system architecture is a key concept in 5G. While it is mainly meant for WiFi and cellular integration, the multi-RAT concept also appears as a reasonable approach for IEEE 802.11p/ITS-G5 integration.

6. Conclusions

After a decade of research and field trials, V2X communication based on IEEE 802.11p/ITS-G5 has developed to a mature technology. Open, international standards play a key role to achieve interoperability; it also brings business benefits and supports government policies and legislation. The release 1 of standards for vehicular communication have been completed in 2014, covering standards for radio, ad hoc networking and transport, facilities layer, security & privacy, and management. Currently, two mature sets of standards for V2X communication exist, namely the C-ITS standards from ETSI and CEN in Europe, and DSCR in the U.S. In Europe, the C2C-CC has derived a profile from the release 1 of C-ITS standards that restrict the large standard set and parameters to a practical set, and complemented missing specifications for security, management and applications. It is expected that the deployment of the C-ITS profile with "Day 1" applications in Europe will be driven by automobile manufacturers and supported by infrastructure pilots, such as the C-ITS corridor Vienna–Frankfurt–Rotterdam. In the U.S., a regulatory process has been initiated to make DSRC mandatory.

For automated driving, the V2X communication release 1 already supports lower automation levels for driver assistance and partial automation (e.g., stop&go), where the driver is still required to resume manual control. For higher automation levels, it expected that two main new functionalities are needed: dissemination of sensor data and cooperative maneuvering. While in release 1 vehicles transmit highly aggregated information, the dissemination of sensor data has higher demands on data rate, latency, and reliability. Also, in the release 1, vehicles typically send data to all neighbors in their vicinity. Cooperative maneuvering may imply to negotiate maneuvers between two vehicles (e.g. for lane merging) or within a small group of vehicles (convoy with C-ACC or platoon). These functionalities can potentially be realized with IEEE 802.11p/ITS-G5 based systems, however it requires a substantial extension of the existing set of standards. The future 5G cellular system promises great enhancements in functionality and performance, including a new radio technology. With the introduction of proximity services (ProSe) into the cellular architecture in the 3GPP LTE standards, the foundation for direct communication among devices as a key functionality for vehicular communication was laid. However, originally ProSe has not been developed with vehicular use cases in mind and requires a re-design. Alternatively, the inherent support for multiple radio technologies in 5G potentially allows for the integration of IEEE 802.11p/ITS-G5 radios into the future 5G cellular systems.

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References

1. Kenney, J. B. (2011): Dedicated Short-Range Communications (DSRC) standards in the United States. Proc. IEEE, 99(7), 1162–1182.
2. Festag, A. (2014): Cooperative Intelligent Transport Systems (C-ITS) standards in Europe. IEEE Commun. Mag., 12(52), 166–172.
3. Car-2-Car Communication Consortium, http://www.car-2-car.org.
4. Amsterdam Group, http://www.amsterdamgroup.eu.
5. Harrer, M., et al. (2015): From research and living lab to implementation of C-ITS. e&i, Elektrotech. Inf.tech. 132(7).
6. Institute of Electrical Engineers (2011): IEEE standard for information technology—telecommunications and information exchange between systems—local and metropolitan area networks—specific requirements, part 11: wireless LAN medium access control (MAC) and physical layer (PHY) specifications, March 2012, http://ieeexplore.ieee.org/servlet/opac?punumber=6178209.
7. Mecklenbräuker, C. F., et al. (2011): Vehicular channel characterization and its implications for wireless system design and performance. Proc. IEEE, 99(7), 1189–1212.
8. Tielert, T., et al. (2011): Design, methodology and evaluation of rate adaptation based congestion control for vehicle safety communications. In Proceedings of IEEE vehicular networking conference (VNC), Amsterdam, Netherlands, November 2011 (pp. 116–123).
9. ETSI (2014): Intelligent Transport Systems (ITS); vehicular communications; basic set of applications; part 2: specification of cooperative awareness basic service, EN 302 637-2, November 2014.
10. ETSI (2014): Intelligent Transport Systems (ITS); vehicular communications; basic set of applications; part 3: specifications of decentralized environmental notification basic service, EN 302 637-3, November 2014.
11. SAE International (2014): Taxonomy and definitions for terms related to on-road motor vehicle automated driving systems, SAE J3016, January 2014, http://standards.sae.org.
12. Prasad, A., et al. (2014): Energy-efficient D2D discovery for proximity services in 3GPP LTE-advanced networks: ProSe discovery mechanisms. IEEE Veh. Technol. Mag., 9(4), 40–50.
13. Next Generation Mobile Networks (NGMN) alliance (2015): NGNM 5G white paper, NGNM 5G initiative, February 2015, 124 p., http://www.ngmn.de/uploads/media/NGMN_5G_White_Paper_V1_0_01.pdf.
14. 5G Infrastructure Public Private Partnership (5G-PPP) (2015): 5G automotive vision, 65 p. (in press), https://5g-ppp.eu/, September 2015.
15. Amsterdam group (2013): Roadmap between automotive industry and infrastructure organisations on initial deployment of Cooperative ITS in Europe, version 1.0, https://amsterdamgroup.mett.nl. June 2013.

[10] Single Carrier Frequency Division Multiple Access.

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