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Automation for On-road Vehicles: Use Cases and Requirements for Radio Design

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Abstract—The support of mission-critical communication (MCC) opens the possibility to implement a broad range of novel applications. V2X communication for traffic safety and automation is, among others, one of these innovative applications expected to bring big benefits to society: accidents are prevented, driving times are reduced, and carbon dioxide is saved. In this regard, we first present a system model and fundamental definitions of reliability, latency and availability. Relying on these definitions, a systematic review of requirements for the huge variety of V2X applications is provided, including insights into the expected evolution towards autonomous driving. The many challenges introduced by V2X use cases are emphasized and compared to today’s wireless system capabilities. Finally, we give our vision on the design of future radio technologies for the support of this kind of communications.

I. INTRODUCTION

Efficient support for machine-type communication (MTC) over wireless is an active research topic gaining increased attention. Especially MTC use cases with mission-critical communication (MCC) requirements are challenging as such services are subject to much tighter latency and reliability requirements than e.g. is the case for mobile broadband (MBB) services. Hence, how to best accommodate both MBB and MCC in the same wireless system presents several new challenges, given the fundamental trade-offs of optimizing for spectral efficiency, latency, and reliability [1]. Examples of wireless system standards with ongoing MTC/MCC related research include (among others) IEEE 802.11p [2] and 3GPP LTE [3], as well as studies on a future 5th Generation (5G) radio standard [4].

A prerequisite for studying MCC over wireless networks is a solid understanding of the use cases and related definitions. In this study we focus on the class of use cases related to vehicular applications. Vehicular use cases include both communication between vehicles, as well as between vehicles and infrastructure (i.e. base stations / access points) or pedestrians, commonly denoted as V2X communication. Given this starting point, we first aim at presenting a generic, yet simple, system model and the related definitions of latency, reliability, and availability. Secondly, a review of V2X applications and their requirements for road safety, traffic efficiency, and infotainment is provided, based on material from ETSI [5] and the US Department of Transportation (DOT) [6]. Especially the characteristics of these different use cases in terms of message rate, message payload size, latency requirements, distinctiveness and reliability are summarized, and put into a wireless system perspective. Furthermore, the expected evolution towards autonomous vehicles is explored [7], [8]. It is identified how such use cases further pushes the requirements of V2X communication. The presented information on use cases offers

a solid basis for definition of realistic traffic models, and their corresponding Quality of Service (QoS) requirements, that can be applied in wireless system research of MCC. Finally, radio design implications for the identified V2X applications are discussed for different wireless system standards. The latter also includes an outlook towards the challenges and related requirements for the upcoming 5G radio system(s), as identified by the EU funded joint research collaboration project METIS [9] and the International Telecommunications Union (ITU) for International Mobile Telecommunications (IMT) for 2020 and beyond [4].

The rest of the paper is organized as follows: Section II presents the generic system model, while the related fundamental definitions for MCC are presented in Section III. V2X use cases and related requirements and models are presented in Sections IV and V. Radio design implications are covered in Section VI, including an outlook towards V2X MCC for 5G. Finally, concluding remarks are summarized in Section VII.

II. SYSTEM MODEL

Fig. 1 depicts the generic system model. It contains a traffic source and a traffic sink that represent the application layer. The traffic source generates data that are transmitted to the traffic sink via the communication system. For open loop applications, the traffic source generates data without awaiting any feedback from the traffic sink, and without knowing if the traffic sink correctly receives the data payloads. For closed loop applications, the traffic sink provides feedback to the traffic source, e.g. acknowledgements (ACK) for each of the sent application layer payloads. In the considered V2X use cases, the traffic source and sink may be either at the vehicle or infrastructure.

The communication system in Fig. 1 represents the complete system that carries the generated data payloads from the traffic source to the traffic sink. The communication system includes at least one wireless link, but could also include multiple wireless links. As an example, if the communication is from vehicle *A* to the infrastructure, and from there to vehicle *B*, then at least two wireless links are part of the communication system. In addition, the infrastructure may include one or multiple backhaul links as well.

The lower layers of the wireless link(s) involve delivering the payload on the air interface. A generic wireless system includes a transmission buffer where the data received from higher layer applications are stored; a scheduler entity allocating radio resources; the transmitter, that tries to adapt the transmission parameters to the variability in the wireless channel, subject to noise and time-variant and frequency-selective fading and interference; and the receiver, where the signal is

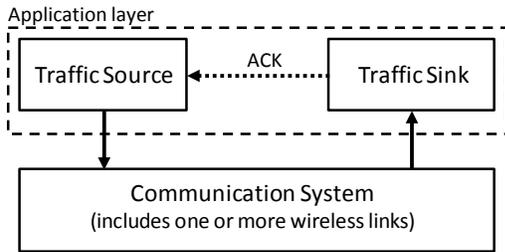


Fig. 1. System model

equalized (and other post-processing procedures) in order to maximize the probability of successful decoding. In case of failed decoding, the transmitter can be asked to retransmit. All these elements introduce variability to the transmission, having an impact on the achievable reliability and latency [1].

III. RELATED DEFINITIONS

A. Reliability definition & service degradation

For an unacknowledged communication, reliability is defined as the probability P that the traffic sink correctly receives a payload of B bits within a maximum latency T [9]. A definition of reliability for acknowledged cases is given by the traffic source correctly receiving an ACK for the payload of B bits within a maximum latency T , with probability P . The acknowledged case is in general more challenging for two reasons: the associated transmission latency of the ACK must be included in the total latency budget, and the ACK message is itself subject to transmission errors.

The definitions above suggest that when the payload of B bits is received after the latency constraint T , it is counted as one error event violating the constraint. Going one step further, one may wonder what happens if the payload is correctly received after $T + \Delta$ (where Δ is small): is the value of the payload completely outdated, or does it still have some value?. The answer is closely related to the nature of the application.

Let us take the example of a typical safety application for V2X, namely the braking warning. Fig. 2 depicts two vehicles driving in the same direction. The vehicle A in front decides to decelerate for a certain reason, e.g. dangerous road conditions or obstacle in the road. In order to avoid a collision, A informs the following vehicle B (via infrastructure or direct vehicle-to-vehicle) about the braking event. The potential crash-avoidance actions that can be performed by B strongly depend on the delay which this vehicle receives the information. In accordance, we present a more sophisticated definition of errors (Fig. 3 (a)):

1) *No error*: The payload is received within a certain latency constraint T . Vehicle B can e.g. apply the brakes to avoid any potential danger. The associated probability of this event is defined as P_0 .

2) *Type-1 error*: The payload is received within a latency constraint $T + \Delta_1$. Vehicle B detects that the collision is unavoidable hence deciding to apply collision mitigation measures such as hard braking plus optimal set up of seat-belts and air-bags. The associated probability of this event is defined as P_1 , where $P_1 > P_0$.

3) *Intolerable error*: The payload is received after the latency constraint $T + \Delta_1$. The collision already occurred

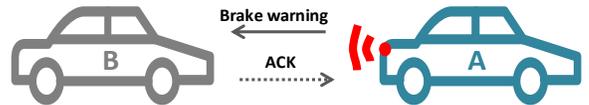


Fig. 2. V2X application example: braking warning

therefore there is no reason to deliver the data.

Notice that the presented definition is generic and can – in principle – allow an arbitrary amount of type- n error cases (see Fig. 3 (b)). For example, one could have allowed e.g. a *no error* case where only soft-braking is applied; a *type-1 error* case where hard-braking and/or evasive manoeuvres are performed; and, finally *type-2 error* where the unavoidable collision measures are executed.

Furthermore, the presented example also works to exemplify the acknowledged reliability definition. Vehicle A can ask B to confirm the reception of the message (i.e. send an ACK). Assuming A knows the (estimate) position of B , vehicle A can apply certain measures to avoid or decrease the impact of a rear-end crash if the acknowledgement is not received within a certain latency constraint.

B. Availability definition

Closely related to reliability, availability is another important metric in V2X communications. Precisely due to their connection, it is difficult to find a consensus in the literature on the definition of these two metrics. We adopt a similar definition as the one in [9].

1) *Space availability/coverage*: Space availability is defined as the percentage of area where a required metric by a certain user is achieved, assuming normal operation of the network. Signal strength and signal-to-noise-and-interference ratio are typical parameters for this metric in radio systems. Space availability is a prerequisite for reliable communication.

2) *Time availability/robustness*: For a certain service area, time availability is defined as the percentage of time the communication system is capable of providing the required service. Infrastructure equipment failure is one of the events with negative impact on time availability. Notice that when the number of error-types in our definition grows, reliability converges to robustness, since the number of admissible re-transmissions increases and the success of the transmission is only limited by the time availability of the vehicular and network infrastructure.

IV. APPLICATIONS AND REQUIREMENTS OF V2X COMMUNICATIONS

Table I presents a detailed summary of the most representative use cases enabled by V2X communications. For each use case, information about the communication type, transmission frequency, maximum end-to-end (E2E) latency, distinctive characteristics (if any), and reliability is itemized. The described use cases information is based on the material from ETSI [5] and US DOT [6], [10].

It is observed from Table I a large variation in terms of requirements for the different use cases. The majority of safety-related applications rely on broadcast of small payloads at 10 Hz transmission rate with a 100 ms latency constraint. Among

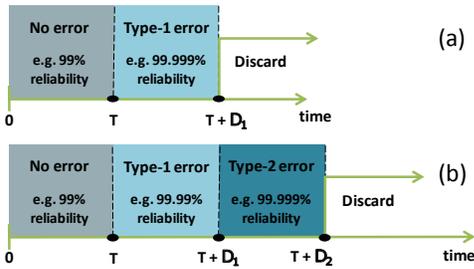


Fig. 3. Categorization of error cases when service degradation is allowed.

these, we have *pre-crash sensing* and *cooperative platooning* as the use cases that, due to their very critical nature, have the tightest communication requirements requiring up to 50 Hz update rate and 20 ms E2E latency. On the other hand, we have infotainment applications (e.g. internet browsing and media streaming) that require high data rates (some Mbps) with relatively relaxed latency constraints (hundreds of ms).

We take the safety-related use cases as an example to give insights into the modelling of MCC in a wireless system. Active road safety applications are categorized into *cooperative awareness* and *road hazard warning* for periodic and event-triggered transmission of safety messages, respectively [5]. These types of messages differ not only in the role and transmission mode, but also in the dissemination policy. The principle of cooperative awareness applications is that each vehicle periodically broadcasts short messages containing real-time information about their position, speed, travelling direction, etc, enabling vehicles to be mutually-aware of their presence and warn the driver when imminent danger is detected. Cooperative Awareness Message (CAM) [11] is the message format standardized for this type of applications and it is typically delivered to all the neighbouring vehicles.

Road hazard warning applications rely on the broadcast of short messages that are triggered after the detection of a hazardous event e.g. obstacle in the way, slippery road. The message format standardized for this purpose is called Decentralized Environmental Notification Message (DENM) [12] which contains information about the detected event, and is delivered to vehicles potentially affected by such event.

Based on the system model presented in Section II, the traffic is modelled as follows: CAMs and DENMs are generated by the traffic sink in a periodic and event-triggered fashion, respectively. For the former, an update rate of 10 Hz is typically used in order to support the majority of safety applications. The packet size typically varies between 50 B to 250 B depending on the inclusion of a low-frequency data container which contains static and not highly dynamic information used to support use cases requiring lower update rate (e.g. 1-2 Hz) [11], [13]. For the DENMs, the packet size varies, being above 1000 B if a detailed description of the event is present [12], [13]. It is worth mentioning that the addition of a security overhead can add up to 250 B additional data to the safety message.

The packet is sent to the system where it is modulated and sent over the wireless channel, and eventually delivered to the traffic sink, which must receive the generated payloads within a certain latency as specified in Table I.

It is worth mentioning that none of the use cases are attached to a specific reliability constraint; however, the different priority levels emphasized in the “distinctiveness” column in Table I describe the relative importance of a particular use case which can be used to give an insight into the required reliability level. Not by coincidence, the use cases requiring (very) high priority are commonly attached to high update rates. The reason why reliability might not be a crucial requirement is that near-term implementations of V2X technology are expected to solely warn and inform drivers about potential danger instead of taking full control of the vehicle. In fact, 802.11p, which is the de-facto standard to support initial V2X safety applications, uses very simple best-effort transmission approaches making it difficult to ensure high reliability especially at high vehicular density and/or high update rates; see [14] - [16], for example. The open literature, however, claims that a communication reliability¹ above 95% is considered good enough to support the majority of safety applications [14], [17].

Availability is another important performance metric for V2X communications; although not specified, it is worth mentioning that high degree of space and time availability is essential especially for safety use cases. Note also that none of the applications specify the need of acknowledged reliability or tolerance to service degradation. This is due to the fact that most of the safety use cases were designed having in mind the capabilities and limitations of 802.11p, which does not allow a straightforward implementation of the presented definitions.

To summarize, there is a large and diverse amount of applications that can be enabled by V2X communication, both safety-related applications requiring MCC and infotainment applications with typical MBB requirements. Notice that none of the use cases simultaneously demand stringent requirements of throughput, latency and reliability. This fact is very relevant from a radio design perspective and will be analysed later.

V. AUTONOMOUS DRIVING VISION

The continuing advances in technology are expected to offer solutions in the vehicular field that further depart from current paradigms. In 2014, the SAE organization published the J3016 standard [19] which aims at providing a common terminology and classification levels for driving automation. Five levels of vehicle automation are defined, ranging from level 0: *No Automation* to level 5: *Full Automation*. We focus on the latter in which the vehicle performs all the driving functions without expected assistance from the driver.

It is claimed that fully autonomous vehicles can entirely penetrate the market between 2025-2030 [20], [21]. To fill the technological gap, there are many projects currently dealing with the definition, development and testing of features for autonomous driving. For example, the AdaptIVE consortium [8] or AutoNet2030, which aims at developing autonomous driving technologies for a 2020-2030 deployment horizon.

Despite these many ongoing efforts, there is still no consensus about what autonomous vehicles are nor what will be needed, from a communication system point of view, to support such use cases. Intuitively, autonomous driving applications will demand more stringent requirements compared

¹Due to the unacknowledged connection-less nature of 802.11p, communication reliability is measured in terms of packet reception rate [14], [18].

TABLE I. V2X USE CASES AND REQUIREMENTS [5], [6], [10]

Application Class	Use Case	Communication type	Update Rate [Hz]	E2E Latency [ms]	Distinctiveness	Reliability [%]
Active Safety	Emergency electronic brake lights	Event-triggered message broadcast informing about braking event	10	100	High priority	Not Specified
	Emergency Vehicle Warning	Periodic permanent broadcast by emergency vehicle	10 in [5] 1 in [10]	100 in [5] 1000 in [10]	Authentication of the sender	
	Motorcycle warning	Periodic permanent broadcast by the 2-wheel vehicle	2	100	-	
	Pedestrian Warning	Periodic message broadcast by road-side sensing infrastructure or human device	1 in [5] 10 in [10]	100	-	
	Wrong way driver	Even-triggered broadcast by vehicle driving in wrong way	10	100	-	
	Stationary vehicle warning	Even-triggered broadcast by immobilized vehicle	10	100	High priority	
	Road work Warning	Even-triggered periodic broadcast by road-side unit	2 in [5] 1 in [10]	100 in [5] 1000 in [10]	-	
	Overtaking vehicle warning	Broadcast of overtaking state	10	100	Large commun. range > 500 m	
	Do not pass warning	Periodic message broadcast of basic safety information	10	100	High priority	
	Lane change assistance	Point-to-point session for cooperation between involved vehicles	10	100	Relative pos. accuracy: < 2 m	
	Lane change warning	Periodic message broadcast of basic safety information	10	100	-	
	Pre-crash sensing	Periodic broadcast + point-to-point session for cooperation between involved vehicles	10 in [5] 50 in [10]	50 in [5] 20 in [10]	Very high priority	
	Left turn warning	Periodic message broadcast of basic safety information	10	100	-	
	Merging traffic warning	Periodic message broadcast of basic safety information	10	100	-	
	Cooperative merging assistance	Point-to-point session for cooperation between involved vehicles	10	100	Relative pos. accuracy: < 2 m	
	Hazardous location	Event-driven broadcast by vehicles detecting the hazardous location	10 in [5] 2 in [10]	100 in [5] 500 in [10]	-	
Intersection collision warning	Periodic message broadcast of basic safety information	10	100	High priority		
Cooperative forward collision warning	Point-to-point two-way communication among vehicles in [5] One way broadcast in [6]	10	100	Relative pos. accuracy: < 1 m; High priority		
Traffic information & efficiency	Traffic light optimal speed	Periodic message broadcasted by road-side infrastructure	2	100	Positioning accuracy: < 2 m	
	Cooperative Platooning	Point-to-point two-way communication among vehicles	2 in [5] 50 in [10]	100 in [5] 20 in [10]	Relative pos. accuracy: < 2 m; High priority	
	In-vehicle signage	Periodic message broadcast by road-side infrastructure	1	500	-	
	Traffic information and recommended itinerary	Periodic traffic information message broadcast by road-side infrastructure	1-10	500	-	
	Map download/update	point-to-point session between vehicle and infrastructure	N/A	500	High data rates	
	Electronic toll collection	Periodic broadcast + point-to-point session between vehicle and infrastructure	1	200	-	
Infotainment	Point-of-interest notification	Periodic message broadcast by road-side infrastructure	2	100	-	
	Browsing, streaming, Download of media	Internet access provided by road-side infrastructure or cellular network	N/A	500	High data rates	
	Instant messaging	Point-to-point session with instant messaging server	N/A	500	-	

to those in Table I. For instance, the METIS consortium has defined a set of communication requirements at the MAC layer for autonomous driving (see Table II) [9]. Notice that the update rates, payload size and traffic type are relatively similar to the presented in Table I, however, with much more stringent requirements of latency, reliability and availability. All these elements represent challenges for the wireless system.

VI. RADIO DESIGN IMPLICATIONS

A. Current communication systems alternatives for V2X

There are various wireless technologies that can match the V2X application requirements more or less effectively [22]. In this section we present a brief overview of the main system alternatives: IEEE 802.11p and 3GPP LTE.

IEEE 802.11p (ITS-G5 in Europe) has been proposed as the standard to support V2X communications. This standard is basically a modified version of the 802.11 specifically designed to deal with the numerous challenges in vehicular environments [2]. The main drawback of 802.11p is its decentralized ad-hoc nature which results in large probability of packet collisions, especially in dense scenarios. Furthermore, the connection-less and unacknowledged mode of communication implies chal-

lenges in establishing very reliable communication, becoming even more difficult in two-way communication scenarios [23]. Finally, it is not clear if it can support the high-bandwidth demands of infotainment applications [24].

Using a cellular-based system such as LTE is another approach gaining increased attention [3], [13], [22], [25]. LTE achieves E2E latencies on the order of 20-40 ms. Similar latency numbers have also been observed in vehicular environments (through simulations) [13], [16]. Based on these studies, it is expected that LTE can support the majority of expected initial applications listed in Table I. Compared to 802.11p, the planned-infrastructure approach inherent in LTE (or in cellular-based systems, in general) results in better performance especially in terms of coverage and communication range, and also better support for applications with different QoS requirements [13], [16]. The lack of support for local data exchange implies, however, dependency on the availability (both space and time) of the cellular infrastructure.

B. Outlook to 5G

Current communication systems will, in principle, be able to support expected near-term implementations of V2X for

safety purposes. However, it is still not clear if they can provide the very high reliability and low latency requirements needed for autonomous driving applications.

The ITU is currently working on defining the overall objectives to be addressed by IMT for 2020 and beyond systems (commonly known as 5G) [4]. Autonomous driving is just one example of the many applications (others include health care, industrial automation, etc [26]) that could benefit by the support of MCC. Motivated by this, the main breakthrough of such 5G system(s) is expected to be the capability to provide flexible and configurable support for multiple applications with very different requirements, ranging from typical MBB services needed for e.g. infotainment applications, to low latency and high reliability for MCC purposes.

As explained in [1], there is a fundamental tradeoff between throughput, latency and reliability; however, the fact that none of the envisioned applications for 5G (V2X field and many others described in [26]) simultaneously demand stringent requirements of these three performance metrics, suggests that it is feasible, although challenging, to design a single wireless system capable of supporting all these services.

VII. CONCLUSIONS

In this paper we have defined key performance indicators for MCC use cases such as latency, reliability, spatial coverage and temporal availability. A review of today's known V2X applications for active road safety, traffic efficiency, and infotainment is presented. Here it is found that the equivalent application layer traffic typically can be represented by open loop models, where the traffic source generate moderate payload sizes of approximately 50-250 bytes at a rate of 1-10 Hz. For most of the applications, the latency requirement is on the order of ~ 100 ms, with only few cases demanding 20 ms. Authorities have not specified exact values for reliability, although distinctiveness in terms of relative priorities are listed. But, it is evident that high reliability as well as high degree of spatial coverage and temporal availability are required. Migration towards future autonomous driving use cases will further tighten the requirements for latency, and especially calling for ultra reliability, as well as correspondingly high spatial coverage and temporal availability. Finally, the feasibility of using wireless standards like IEEE 802.11p and 3GPP LTE have been elaborated, as well as an outlook towards 5G. Among others, 5G is estimated to be capable of meeting the challenging requirements of supporting larger variety of multiple types of services, as compared to what is feasible with today's wireless systems.

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TABLE II. METIS REQUIREMENTS FOR V2X [9]

Requirement	Value
Payload size (MAC)	1600 Bytes
Latency	< 5 ms
Update Rate	5 - 10 Hz for periodic and event-triggered messages
Reliability	99.999 %
Availability	~ 100 %
Device density	Vehicular: 100-1000 dev/km ² ; Pedestrians: 150-5000 dev/km ²

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