Chapter 16
LTE for Vehicular Communications

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Abstract The cellular communication networks standard 3rd Generation Partnership Project (3GPP) Long Term Evolution (LTE) offers low latencies and high throughputs simultaneously, thus enabling more bandwidth-demanding and real-time critical services for end-users. This is of particular interest for vehicle manufacturers who in the future intend to offer a huge variety of cooperative driver assistance services with manifold quality of service requirements. This chapter analyzes the suitability of LTE as a wireless transmission technology for future vehicular services of the categories *Infotainment*, *Comfort*, *Traffic Efficiency*, and *Safety*. The investigations are based on extensive LTE system-level simulations under different load conditions and network deployments as well as on a theoretical delay analysis. Focus is set on transmission delays and reliability aspects under various quality of service settings. The results show that an accurate selection of the LTE quality of service parameters is crucial in order to meet the delay and reliability requirements of future automotive applications, especially in high-load network conditions.

Keywords VANET • LTE • LTE-A • Safety applications • Comfort applications • Traffic-efficiency applications • Infotainment applications • Cooperative Awareness Messages (CAMs) • Decentralized Environmental Notification Messages (DENMs) • Floating Car Data (FCD) • Periodic Driver Assistance Service (PDAS) • Voice over LTE (VoLTE) • Voice Recognition (VR) • Resource Block (RB) • Quality of Service Class Identifier (QCI) • Evolved Multimedia

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Broadcast Multicast Service (eMBMS) • Vehicle-to-vehicle (V2V) • Vehicle-to-infrastructure (V2I) • Vehicle-to-X (V2X) • Vehicle-to-device (V2D) • Quality of Service (QoS)

16.1 Introduction

Improving traffic safety, efficiency, and driver's comfort becomes more and more important for modern vehicles. At the same time, the demands for high data rate information and entertainment services grow.

Modern vehicles are increasingly equipped with on-board advanced driver assistance services (ADAS) which process data from numerous on-board vehicle sensors. However, to further improve ADAS systems, it is required to enlarge the range of the sensors mounted at the vehicle by incorporating also information from the outside world. This can be obtained from cooperation with other vehicles or road infrastructure, known as V2V, vehicle-to-infrastructure (V2I), infrastructure-to-vehicle (I2V), or vehicle-to-X (V2X) communications. The IEEE 802.11p [36] standard specifies the communication technology for ITS applications in Vehicular Ad Hoc Networks (VANETs). Its advantages are easy deployment, low costs, mature technology, and the capability to natively support V2V communications in ad hoc mode. Nonetheless, this technology suffers from scalability issues and low penetration, unbounded delays, and lack of deterministic quality of service (QoS) guarantees [15]. Due to its ad hoc connectivity focus, its limited radio range and without a pervasive roadside communication infrastructure, IEEE 802.11p can only offer intermittent and short-lived V2I connectivity. These concerns motivate the investigation of wireless access technologies to support advanced V2I and V2V communications in vehicular environments. LTE [9] is the most promising wireless broadband technology that provides high throughput and low latency for mobile services. Like all cellular systems it benefits from a large coverage area, high penetration rate providing the economical basis for short development cycles, and high velocity terminal support.

LTE particularly meets the high-bandwidth demands and QoS requirements of a category of vehicular applications known as *Infotainment* (information and entertainment). This category includes traditional and emerging Internet applications. Moreover, the delivery of driving context-related information for *Traffic Efficiency* applications and applications of the *Comfort* class implies less stringent delay requirements without exhausting the LTE system resources. Nevertheless, the LTE capability to support applications specifically conceived for the vehicular environment to provide *Safety* services is still an open issue. Both *event-triggered warnings* (e.g., generated in case of accidents) and *periodic messages* (exchanged among vehicles for cooperative driving applications) belong to this category. The main concern comes from the centralized LTE architecture. Even for a localized V2V data exchange, communications always cross infrastructure nodes with negative consequences on message latency, especially for *Safety* applications. In addition, in dense traffic areas, the heavy load generated by periodic message transmissions from several vehicles strongly challenges the LTE capacity and may penalize the delivery of traditional applications.

In this chapter the suitability of LTE as a wireless transmission technology for future automotive off-board services is analyzed. In Sect. 16.2 the typical V2V and V2I service classes are introduced and their QoS requirements are defined. Section 16.3 explains the LTE architecture and shows the application in an automotive environment. Its suitability for non-safety services is evaluated in Sect. 16.4. In particular, the impact of specific LTE quality of service class identifier (QCI) settings on the transmission delays and packet discard rates are analyzed under various load conditions. Simulations to assess the performance of LTE for *Safety* services, along with an overview of literature investigations and their limitations are presented in Sect. 16.5. The results allow a consolidated view on the suitability of LTE for vehicular communications, its strengths and critical aspects. In Sect. 16.6, a comparison between IEEE 802.11p and LTE for automotive services is given. An outlook to future research topics is presented in Sect. 16.7. Finally, conclusions are drawn in Sect. 16.8.

16.2 Characterization of the Applications and Their Requirements

The considered off-board services are classified into four groups: *Infotainment*, *Comfort*, *Traffic Efficiency*, and *Safety*. However, these service categories vary considerably in their QoS requirements, such as end-to-end (E2E) transmission delay, jitter, and the overall required throughput.

16.2.1 Infotainment Applications

Infotainment applications incorporate entertainment and information related applications, such as Internet audio streaming, video streaming, and information services, which are already part of modern premium vehicle systems. Content download, media streaming, web-browsing, social networking, blog uploading, gaming, and access to different cloud services are typical *Infotainment* applications. In the future, this class will be extended to video-related services that offer advanced video-based information, such as bandwidth-consuming video surveillance (VS) [33] or video traffic information services. As of today, streaming applications of this class typically have fixed source rates and, hence, constant throughput requirements on the transmission chain that range from data rates of 92 kbit/s for low-rate audio streaming to 3 Mbit/s for high-definition video information services. In addition, the one-way E2E delay (δ_{E2E}) requirements typically vary between 100 and 600 ms.

16.2.2 Comfort Applications

Applications of the *Comfort* class aim to ease the driver's daily life. They include context-related driver information, such as voice recognition (VR), information about the current traffic situation (live traffic information), and location-based services, as well as remote software updates for the vehicle. As the majority of today's applications are run on consumer electronic (CE) devices, applications of the *Comfort* class are often based on Internet web-services which use reliable transport layer protocols for the data transmission, such as TCP/IP (transmission control protocol, Internet protocol). By definition, such web-services are less time-critical with delay constraints in the order of seconds and classified as interactive or background services based on best-effort traffic patterns with no stringent QoS requirements. Here, the application is fully responsible for the successful transmission of the data packets.

16.2.3 Traffic Efficiency Applications

Traffic Efficiency applications aim to optimize flows of vehicles by reducing travel time and traffic congestion. Similar to *Comfort* class services, applications of the *Traffic Efficiency* class are based on Internet web-services and, hence, have less stringent QoS requirements. However, their quality gradually degrades with increasing packet loss and delay. In this class, the decentralized floating car data (FCD) service and its extension, extended floating car data (XFCD) [19, 35], require periodic transmissions of information collected by vehicles from internal and external sensors (e.g., information provided at the CAN bus, in-vehicle camera, environmental monitoring sensors) to remote management servers. They process the collected data, monitor and predict traffic congestion, and send up-to-date traffic information back to the vehicle's navigation system in order to suggest alternative routes. Besides the collection of the floating car data, vehicles are able to request traffic related information with respect to their actual context from a service provider. However, two different kinds of services for such information are defined: *event-driven* services and *periodic* services, referred to as periodic driver assistance services (PDAS) in the following. Event-driven services encompass traffic and navigation related information, such as alternative route suggestions, construction site information, or traffic light cycle information. For PDAS, aggregated and relevant off-board information about the surroundings of the vehicle is sent to the vehicle's on-board component periodically, such as periodic information about the average velocity in a certain route section.

16.2.4 Safety Applications

Safety services aim at reducing the risk of car accidents and have timeliness and reliability as the major requirements. Two main types of safety messages have been standardized. Their transmission can be periodic or event-triggered. In the European Telecommunications Standards Institute (ETSI) documents [25] they are referred to as Cooperative Awareness Messages (CAMs) [22] and Decentralized Environmental Notification Messages (DENMs) [23], respectively. Basic Safety Message (BSM) is the terminology used in [53] for both periodic and event-triggered messages.[1]

CAMs, also known as *beacons* or *heartbeat* messages, are short messages periodically broadcast by each vehicle to its neighbors to provide information on presence, position, kinematics, and basic status. DENMs are event-triggered short messages broadcast to alert road users of a hazardous event.

Both CAM and DENM messages are delivered to vehicles in a particular geographic region: the immediate neighborhood (*awareness range*) for CAMs, and the area potentially affected by the notified event (*relevance area*) for DENMs, such as congestion or hazard warning. The relevance area might span over several hundred meters for DENM message distribution. The capability of transmitting a message to nodes satisfying a set of geographical criteria is called *geocast* and represents together with reliability and low-latency delivery a crucial requirement of the typical temporal- and spatial-relevant vehicular applications.

16.2.5 Summary of QoS Requirements

Table 16.1 summarizes the QoS requirements of the different application classes in terms of E2E delay, throughput, reliability, and required connectivity type. The E2E delay δ_{E2E} is the overall transmission delay which is composed of the delay contributions of the on- and off-board application units, i.e., in the vehicle and the backend server, and the overall communication path between the transmitter (e.g., vehicle) and the receiver (e.g., roadside unit). Reliability represents the requirement for a high successful packet delivery ratio (successful and in-time message transmission) which is crucial for *Safety* applications and for some *Traffic Efficiency* applications. Applications of the *Comfort* domain and *Traffic Efficiency* applications typically rely on best effort traffic patterns, since the information contained in the messages is rather informal compared to services of the *Safety* domain and, hence, has no strict time constraint.

[1] See Chap. 5 for a more detailed overview of those messages.

Table 16.1 Overview of the QoS requirements of the different application classes

Application class	Main requirements	Connectivity type	Examples
Infotainment	High throughput, medium-to-low latency	V2V, V2I, I2V	Web-browsing, VS, file sharing, gaming, e-mail
Comfort	Medium-to-low reliability	V2I, I2V	VR, live traffic information, remote software updates
Traffic efficiency	Medium-to-high reliability	V2I, I2V	XFCD, PDAS
Safety	High reliability, low latency ($10\,\text{ms} < \delta_{\text{E2E}} < 1\,\text{s}$)	V2V, V2I, I2V	*CAM-based:* Emergency vehicle warning, intersection collision warning, slow vehicle indication *DENM-based:* Emergency electronic brake light, collision risk warning, visibility

16.3 LTE Technology Overview

In the following section, first a comparison of LTE to other radio access technologies for vehicular connectivity is given, followed by an overview of the core features of LTE, the LTE architecture, and the QoS system concept. Table 16.2 compares the traditional vehicular technologies Wi-Fi and 802.11p with the 3GPP technologies Universal Mobile Telecommunications System (UMTS), LTE, and LTE Advanced (LTE-A). Although initially not designed for automotive applications, the enhancements in LTE may support a huge variety of novel vehicle services at acceptable QoS. LTE and LTE-A represent the most promising cellular systems for vehicular connectivity. Commercial LTE deployments have started in Europe in 2010 and LTE networks are successfully operated in many countries all over the world.

16.3.1 Overview

The overall LTE system is characterized by a flat all-IP architecture with a reduced number of network entities and a separation of the control plane and user plane traffic. IP-based data, voice, and signaling transmissions simplify extendibility with respect to previous cellular networks (UMTS and Global System for Mobile Communications (GSM)). Thanks to its flat architecture, LTE can provide round trip times (RTTs) theoretically lower than 10 ms, and transfer latency in the radio access of up to 100 ms. Measurements in current live LTE networks typically show RTTs between 15 and 60 ms. Providing low latencies also in high traffic load situations is essential for delay-sensitive vehicular applications.

Table 16.2 Main candidate wireless technologies for the vehicular connectivity

Feature	Wi-Fi	802.11p	UMTS	LTE	LTE-A
Channel bandwidth (MHz)	20	10	5	1.4, 3, 5, 10, 20	up to 100
Frequency bands (GHz)	2.4, 5.2	5.86, 5.92	0.7–2.6	0.7–2.69	0.45–4.99
Bit rate (Mbit/s)	6–54	3–27	2[a]	Up to 300	Up to 1,000
Coverage	Intermittent	Intermittent	Ubiquitous	Ubiquitous	Ubiquitous
Capacity	Medium	Medium	Low	High	Very high
Mobility support	Low	Medium	High	Very high (up to 350 km/h)	Very high (up to 350 km/h)
QoS support	Enhanced Distributed Channel Access (EDCA)	EDCA	QoS classes and bearer selection	QCI classes and bearer selection	QCI classes and bearer selection
Broadcast support/multicast support	Native broadcast	Native broadcast	Through Multimedia Broadcast Multicast Service (MBMS)	Through evolved MBMS (eMBMS)	Through evolved MBMS (eMBMS)
V2I support	Yes	Yes	Yes	Yes	Yes
V2V support	Native (ad hoc)	Native (ad hoc)	No	No	Yes (through device-to-device (D2D))
Market penetration	High	Low	High	High	Potentially high
Transmission costs	Low	Low	High	High	High

[a] Higher data rates can be achieved with the UMTS enhancements HSPA and HSPA+

The overall LTE architecture is composed of the evolved UMTS terrestrial radio access network (E-UTRAN), which is the radio access part of LTE and the Evolved Packet Core (EPC) which encompasses all core network entities (cf. Fig. 16.1).

16.3.2 LTE Air Interface

The radio access network is composed of evolved NodeBs (eNodeBs), which are responsible for radio resource and handover management. The LTE air interface has the flexibility to support frequency division duplex (FDD), time division duplex (TDD), and half-duplex FDD schemes. It provides scalable channel width ranging from 1.4 to 20 MHz.

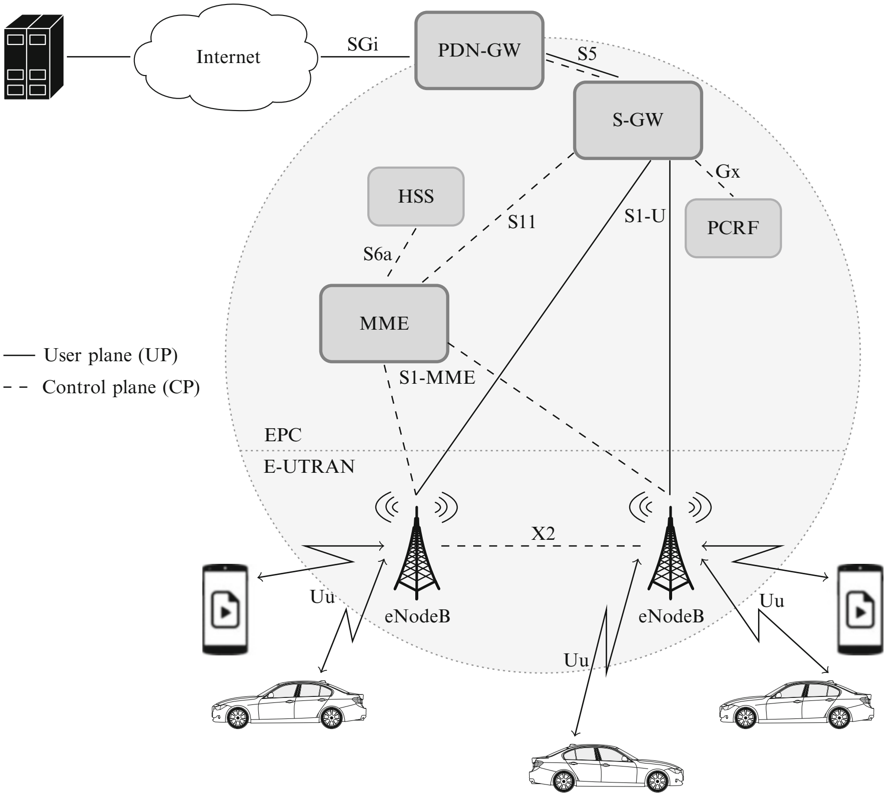

Fig. 16.1 LTE architecture: access network (E-UTRAN) and core network (EPC) entities

Orthogonal frequency division multiple access (OFDMA) is used in the downlink (DL) to fulfill the E-UTRAN performance requirements. With the use of orthogonal frequency division multiplexing (OFDM), frequency-selective fading of the multi-path channel can be exploited and low-complexity receivers can be used. Furthermore, due to a sub-carrier spacing of 15 kHz, degradations from phase noise and Doppler (for 250 km/h at 2.6 GHz) can successfully be avoided even with 64 quadrature amplitude modulation (QAM). LTE uplink (UL) uses single carrier frequency division multiple access (SC-FDMA) due to its peak-to-average power ratio (PAPR) allowing low power consumption and higher efficiency at the User Equipment (UE). Apart from a lower PAPR, the orthogonality inherited from OFDM reduces intra-cell interference. As a result, the role of power control becomes crucial to provide the required signal-to-interference-plus-noise ratio (SINR) according to QoS requirements while controlling the interference caused to neighboring cells at the same time [20, 47].

Multiple-input and multiple-output (MIMO) techniques are used to improve the spectral efficiency by a factor of 3-4 compared to 3.5 generation (3.5G) systems even at high terminal speeds, making LTE particularly efficient in challenging and dynamic propagation environments like the vehicular one.

Radio resources are centrally managed by an eNodeB at every transmission time interval of 1 ms duration, with the aim of satisfying QoS requirements while increasing channel utilization. The packet scheduler at the eNodeB plays a key role, since it selects the traffic flow based on the related QoS requirements as specified by the QCI. LTE supports quadrature phase-shift keying (QPSK), 16 QAM, and 64 QAM. For the uplink, the last one is optional. Adaptive modulation and coding (AMC) decides the appropriate modulation and coding scheme based on feedback from the mobile terminals on the channel quality [47].

16.3.3 Evolved Packet Core

The LTE core network, EPC, is responsible for the authentication, mobility management, bearer control, charging, and QoS control. It is composed of three main entities: the Mobility Management Entity (MME), the Serving Gateway (S-GW), and the Packet Data Network Gateway (PDN-GW), cf. Fig. 16.1.

The MME is the key control entity for the LTE network. It is mainly responsible for tracking, paging and storing the position information of the users, as well as authentication of the users in collaboration with the Home Subscriber Server (HSS). Furthermore, it is involved in the bearer activation/deactivation procedure and responsible for selecting the S-GW.

The task of the S-GW is routing, data forwarding, and charging by coupling with the policy and charging rules function (PCRF). It also acts as an anchor for mobility during inter-eNodeB handover and mobility between the other 3GPP technologies.

The PDN-GW is the outgoing entity that allows communication with IP and circuit-switched networks. It is responsible for packet filtering of each user, policy enforcement and charging support. The mobile terminal can have connections to multiple PDN-GWs for accessing multiple packet data networks (PDNs).

LTE also supports high-quality multicast and broadcast transmissions through the eMBMS [11], in the core and in the radio access network. It offers the possibility of sending the data only once to a set of users registered for the offered service, instead of sending it to every node separately.

16.3.4 LTE QoS Classes and Mapping for Vehicular Services

In the LTE standard the different QoS requirements of multiple applications are supported by establishing different bearers within the evolved packet system (EPS) [34]. Here, an EPS bearer is defined as the virtual connection between the terminal and the PDN-GW. Each EPS bearer is associated with a certain QoS setting defined by the QCI as well as an allocation and retention priority (ARP). QCI refers to a set of packet forwarding treatments, for example resource type, priority, acceptable packet loss rate (PLR), and delay budget. The priority, packet delay budget, and packet loss rate define how the bearer shall be handled in terms of scheduling policy, queue management, and rate shaping policy. All packet flows that are based on one bearer are treated in the same manner.

The resource type is categorized into two groups: guaranteed bit rate (GBR) bearers and non-GBR bearers. A GBR bearer is used for services that require a certain minimum bit rate which is achieved by permanently allocating dedicated bandwidth resources. Higher bit rates may only be allowed if resources are available. Conversational services like voice over LTE (VoLTE) or video-telephony using semi-persistent scheduling are examples for this group. For non-GBR bearers no specific bit rate is guaranteed, i.e., no bandwidth resources are permanently allocated. This is the case for applications such as web-browsing or file transfer protocol (FTP) services. In total, nine different QCIs with specific QoS requirements have been specified in 3GPP LTE Release 8 (cf. Table 16.3). In addition operator specific QCIs can be defined. An ARP is used by admission control to decide whether a bearer creation or modification request can be accepted or needs to be rejected due to resource limitations.

Although the QCI classes have initially not been designed for vehicular applications, an assignment of the vehicular application classes introduced in Sect. 16.2 to the QCI classes defined by 3GPP based on their QoS requirements can be performed. Applications of the *Comfort* and *Traffic Efficiency* domain are usually based on web services using a TCP-based transmission of the information. Depending on the priority, a non-GBR bearer with a QCI class 6, 8, and 9 can be selected for these applications. For *Infotainment* services, the QCI class selection depends on the traffic patterns of the applications. Streaming services with fixed bit rate requirements (such as video streaming) demand a GBR bearer with a QCI class 2 or 4. Dynamic streaming applications, such as adaptive Hypertext Transfer Protocol (HTTP) streaming, are more relaxed in their QoS requirements and can be allocated to a non-GBR bearer with a QCI class 6. In contrast to the previously mentioned

Table 16.3 Standardized QCI characteristics, [6]

QCI	Bearer type	Priority	Packet delay (ms)	PLR	3GPP sample application
1	GBR	2	100	10^{-2}	VoLTE call
2		4	150	10^{-3}	Video call
3		3	50		Online gaming (real-time)
4		5	300	10^{-6}	Video streaming
5	Non-GBR	1	100		IP Multimedia Subsystem (IMS) signaling
6		6	300		Video, TCP-based services
7		7	100	10^{-3}	Voice, video, interactive gaming
8		8	300	10^{-6}	Video, TCP-based services
9		9			

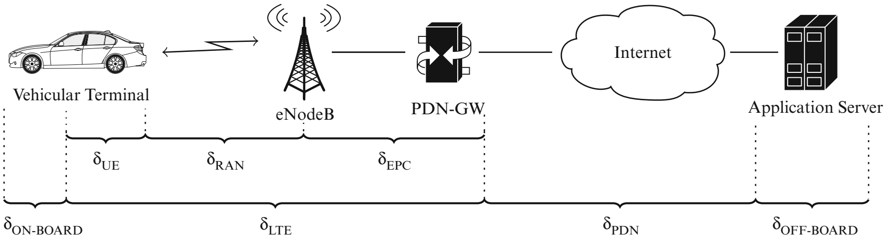

Fig. 16.2 Overall transmission chain

classes, most applications of the *Safety* class rely on the exchange of CAM and DENM messages and thus have strict end-to-end delay requirements of less than 100 ms. However, CAM and DENM messages need to pass the radio access link in the uplink and downlink direction, as well as the core network components, which may result in a total guaranteed delay of more than 100 ms. Hence, none of the defined QCI classes fulfills the requirements of the *Safety* services.

16.3.5 Overall Transmission Chain

A general overview of the overall E2E user plane transmission chain of automotive off-board services is given in Fig. 16.2. It consists of an off-board component located at an external backend server in the Internet and an on-board component in the vehicle. Both service components exchange data via the LTE system and an external PDN. The latter is usually the general Internet transmission path. Therefore, the one-way E2E transmission delay δ_{E2E} is composed of

$$\delta_{\text{E2E}} = \delta_{\text{ON-BOARD}} + \delta_{\text{LTE}} + \delta_{\text{PDN}} + \delta_{\text{OFF-BOARD}}\,,$$

where $\delta_{\text{ON-BOARD}}$ and $\delta_{\text{OFF-BOARD}}$ are the delays contributed by the on- and off-board application and δ_{LTE} and δ_{PDN} are the transmission delays induced by the LTE system and due to Internet routing, respectively. The latter has been thoroughly investigated in [62]. The delay of the LTE system can be further split into the terminal (UE) component δ_{UE}, the Radio Access Network (RAN) component δ_{RAN}, and the EPC component δ_{EPC} as

$$\delta_{\text{LTE}} = \delta_{\text{UE}} + \delta_{\text{RAN}} + \delta_{\text{EPC}}\,. \tag{16.1}$$

The delay of the LTE system δ_{LTE} also depends on the traffic load and increases if packets cannot be scheduled immediately and have to be buffered. This aspect relates to the whole chain of network nodes and transport lines. Note that in the following the QoS performance analysis will focus only on the LTE system component.

16.4 LTE for Non-safety Applications

In this section, the suitability and the performance of LTE as a wireless transmission technology for non-safety applications of the *Infotainment*, *Comfort*, and *Traffic Efficiency* class are investigated. Safety applications entailing different traffic patterns and requirements are discussed in Sect. 16.5. In particular, the impact of specific LTE QCI settings on the transmission delays and packet discard rates for various automotive services is analyzed. Furthermore, the overall load and performance of the LTE system in typical deployments is investigated. This performance analysis is based on extensive LTE system-level simulations under various load conditions and network deployments as well as on thorough theoretical investigations.

16.4.1 Simulation Assumptions

The simulations have been performed by using a real-time network simulator proposed in [60]. The simulator models a cellular LTE system with the number of cells depending on the scenario and concurrent users with realistic traffic patterns based on a system-level simulation paradigm. In order to guarantee meaningful statistical data, ten simulation runs per scenario with a simulated time of 1 h have been performed.

16.4.1.1 Terminal Classes

Different terminal classes have been defined to simulate realistic load scenarios. The class of *mobile terminals* represents all typical CE devices equipped with an LTE broadband modem, such as smartphones or portable computers. Additionally, *vehicular* terminals cover a class of terminals supporting the applications of automotive service classes. In particular, two types of vehicular terminals have been introduced: *fully equipped* vehicles that are able to request all services of the *Infotainment*, *Comfort*, and *Traffic Efficiency* classes, and *basic-equipped* vehicles that are able to request all services from the *Comfort* class.

The basic assumption is that the public LTE network serves vehicular as well as non-vehicular (referred to as mobile) terminals. A base traffic load has been assumed that represents the traffic originated from standard subscribers. On top of that base load, additional traffic from vehicular users has been simulated.

16.4.1.2 Deployment Scenarios and Traffic Load

Three characteristic scenarios in a typical LTE network deployment with specific road types have been considered: an *urban*, *rural*, and *highway* scenario. Figure 16.3 shows the simulation cell layout restricted to the coverage area of one eNodeB in each scenario. The total number of terminals, i.e., the sum of *mobile* and *vehicular terminals*, in each scenario has been derived from measurements of GSM, UMTS, and LTE live networks, cf. [43]. The simulated vehicle density has been calculated from the average vehicle frequency per day on German roads (cf. d_{20} in [18]). The velocity of each terminal is individual with a standard deviation of 10 %. The mean velocity values, introduced in the following, depend on the local scenario as well as on the road types and have been derived from [45].

The *urban* scenario (cf. Fig. 16.3a) represents a typical German inner city scenario, which is constructed by seven eNodeBs deployed in a hexagonal layout with an inter-site distance of 150 m. In accordance with current LTE network deployments in Germany, the short-range 2.6 GHz LTE spectrum has been applied. Due to the small cell-size, the overall number of simulated terminals is rather low and consists of 14 *fully*- and 14 *basic-equipped* vehicles, and 56 *mobile terminals* generating the base load. Vehicular terminals move in a bounce-back Manhattan grid model at a mean velocity of 30 km/h, whereas the *mobile terminals* are following a random walk movement model at a mean velocity of 5 km/h.

For the *rural* scenario, three eNodeBs operating in the long-range 800 MHz LTE frequency band with an inter-site distance of 3.3 km have been considered. The simulated area contains two types of roads (cf. Fig. 16.3b): urban roads and rural roads. Urban roads are deployed in a Manhattan grid model similar to the *urban* scenario. Vehicles on rural roads drive with a mean velocity of 80 km/h, while vehicles on urban roads travel with a mean velocity of 30 km/h. *Mobile terminals* move with a pedestrian velocity of 5 km/h. In total, 123 *fully*- and 102 *basic-equipped* vehicles as well as 60 *mobile terminals* for base load generation have been simulated in the rural environment.

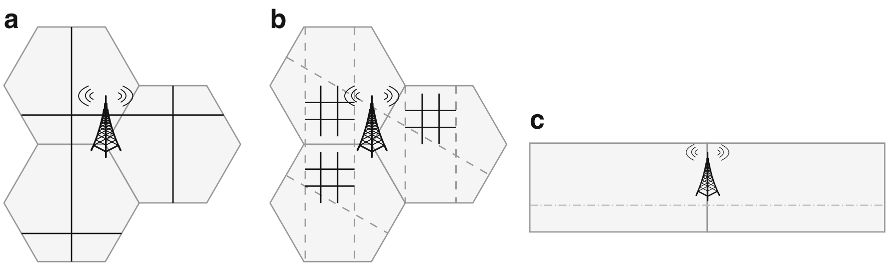

Fig. 16.3 Simulated scenario setups: Urban roads (——), rural roads (– – –), highway roads (–·–·–).

In the *highway* scenario (cf. Fig. 16.3c), the simulation area is constructed by two eNodeBs operating on the long-range 800 MHz LTE frequency band with an inter-site-distance of 25 km. The long inter-site distance in this scenario results from live network planning tools with LTE propagation models for flat environments and represents, with such a large cell size, a worst case scenario from a capacity perspective. In hilly terrains, the resulting inter-site distance is smaller, typically around 10 km. For capacity demands or the mitigation of higher in-car penetration loss due to shielded windows, further reduction of the inter-site distance is necessary. The eNodeBs are deployed in a straight line with their main antenna beams along the highway. In this scenario all terminals, i.e., mobile and vehicular, travel at a mean velocity of 130 km/h, which is a typical assumption for German highways. Here, the *mobile terminals* are assumed to be located inside the vehicle and coupled to the roof-top antenna of the vehicle. This is an approach that is considered in modern vehicles, in order to avoid mobile signal degradation of CE devices inside vehicles due to the penetration loss of the vehicle body. The simulated terminals are partitioned in 112 *fully*- and 148 *basic-equipped* vehicle terminals as well as 52 *mobile terminals*.

16.4.1.3 System Model

The simulations have been performed in FDD mode. FDD is the mode that is typically used in commercial European LTE networks. The physical layer model is simplified but still exact; it provides frequency-selective and time varying SINR values for every resource block (RB) consisting of a transmission time interval (TTI) of 1 ms duration and a bandwidth of 180 kHz. A total bandwidth of 10 MHz for each direction, uplink and downlink, has been used with frequency reuse factor of 1. In order to simulate realistic channel characteristics, interference from the surrounding cells has been taken into account via the mirror-and-shift technique. In this model the signals within the cells of interest are copied, shifted in time and frequency and introduced as interference signals from outside the simulated area. In all simulation scenarios a proportional fair scheduler has been applied [34]. The essential network parameter settings are summarized in Table 16.4.

16.4.2 Simulated Services and Their Requirements

In order to evaluate the QoS performance of the LTE network under realistic load conditions, a total number of 14 DL and 11 UL automotive services of the *Infotainment*, *Comfort*, and *Traffic Efficiency* domain have been simulated [43]. These services include a variety of current and future automotive off-board services as well as standard applications, such as web-browsing or e-mail. Since most of the

Table 16.4 Network parameters for the different simulation scenarios

Parameter	Urban	Rural	Highway
Duplexing mode	FDD		
System bandwidth	10 MHz UL/10 MHz DL		
Frequency band	2.6 GHz	800 MHz	800 MHz
Inter-site distance	150 m	3.3 km	25 km
eNodeB antenna gain	14 dBi		
eNodeB antenna beamwidth H/V	70°/10°		
eNodeB antenna height	10 m	35 m	50 m
eNodeB antenna downtilt	15°	6°	3°
UE antenna height	1.5 m		
UE antenna gain	0 dBi		
UE antenna pattern	Omni-directional		
Antenna configuration	2 × 2 (receive (Rx)/transmit (Tx))		
DL scheduling	Proportional fair with QoS support		
UL scheduling	Proportional fair with QoS support		
DL MIMO mode	Rank–adaptive closed–loop spatial multiplexing		
DL channel quality indicator reporting	Sub–bandwidth 3 RB, period 5 TTIs		
UL user bandwidth	Adaptive		
DL Tx power	46 dBm		
Max. UL Tx power	24 dBm		
UL power control	Open loop fractional power control [8, 47]		
Target uplink Rx power level P_0 [8]	−66 dBm	−85 dBm	
Uplink Pathloss Compensation factor α [8]	0.8		
Noise figure eNodeB/UE	3 dB/7 dB		

services follow similar characteristics and show similar behavior, focus has been set on a representative composition of selected applications. These services and their corresponding traffic patterns are summarized in Table 16.5.

The traffic properties of the different services are characterized by the packet size p_{size} as well as their transmission pattern. Note that most of the considered non-streaming applications trigger data transmissions in random time intervals t with the exponential probability density function $f(t) = \lambda e^{-\lambda t}$, where $t \geq 0$ and $\lambda = t_{\text{request}}^{-1}$. Here, t_{request} denotes the mean inter-request time of the respective service. Moreover, streaming services are characterized by a specific source rate R_{data}. Additionally, each service is mapped to a specific QoS setting given by a QCI and a corresponding packet delay budget. The latter specifies how long a packet remains in the transmission queue before timers expire and it is discarded. The QCIs are chosen in such a way that the corresponding packet delay budget matches the

Table 16.5 Analyzed services with QCI mappings (cf. [6]) and traffic properties

Application	Service class	Link	QoS		Traffic properties		
			QCI	Packet Delay Budget (ms)	p_{size} (kbit)	$t_{request}$ (s)	R_{data} (kbit/s)
VS [43]	*Infotainment*	UL, GBR	2	150	200	–	1,600
		UL, non-GBR	10	60,000	200	–	1,400
VoLTE [48]	*Infotainment*	UL, DL	1	100	4	–	12.2
FTP [48]	*Infotainment*	DL	10	60,000	$\leq$42,000	30	–
VR [30]	*Comfort*	UL	8	300	65	600	–
		DL	10	60,000	3.8	600	–
XFCD [43]	*Traffic efficiency*	UL	8	300	3.8	300	–
PDAS [43]	*Traffic efficiency*	DL	8	300	107	60	–

delay requirements of the corresponding service. For the simulations one additional QCI (i.e., QCI 10) has been introduced that can be one of the operator specific QCIs representing a best-effort traffic pattern with no strict delay requirements.

16.4.2.1 Infotainment Services

For the *Infotainment* domain the investigations have been focused on a quite resource-demanding application, thus indicating a worst-case scenario. VS represents a service that monitors the environment of the vehicle by means of camera systems. Off-board services like off-board traffic sign recognition use this video data for processing. Furthermore, the transmission of video streams between vehicles has been investigated to enhance safety while driving [33]. Note that VS services are only implemented in *fully-equipped* vehicles. The overall traffic flow has been separated into two bearers with different QoS characteristics. The first bearer represents a GBR bearer of QCI 2, which is the QCI class for live streaming services according to [6], with a constant source data rate of $R_{data} = 1.6\,\text{Mbit/s}$. This represents 8 (fps) of an I-frame only video stream encoded with H.264, which is the minimum required number of frames in the presumed off-board VS service. The second bearer is a non-GBR bearer serving additional traffic of 7 fps with a data rate of $R_{data} = 1.4\,\text{Mbit/s}$ and the same encoding. This bearer is based on QCI 10 with relaxed delay requirements, since packets transmitted by this bearer contain additional frames that are used to improve the quality of the off-board services, but not necessarily required for a basic functionality of the off-board services.

Additionally, two services with different QoS demands have been analyzed: VoLTE and FTP. VoLTE represents a two-way service with stringent delay requirements. According to [6] VoLTE services are based on QCI 1, featuring the most stringent delay requirements in these investigations. FTP presents a typical background service that is not delay-sensitive and thus mapped on QCI 10. In order to accurately model this application, FTP packets of variable size p_{size} have been simulated according to the truncated log-normal distribution [48] with a maximum size of 42 Mbit.

16.4.2.2 Comfort Services

In the *Comfort* domain the results for one typical service are presented: VR, a hybrid, two-way communication service representing a speech-to-text application, which is implemented in most modern premium-vehicles [49]. For this service an on-board component records the driver's voice command and transmits the voice pattern in small data chunks of $p_{\text{size}} = 65$ kbit to the off-board component (cf., [30]). The off-board component performs the voice recognition and sends the identified text message back to the on-board component of the application. Since the VR service is based on a TCP/IP web-service, the uplink transmission path is based on QCI class 8 with a packet delay budget of 300 ms. The downlink information is not time-critical, thus relaxed delay boundaries of QCI 10 can be assumed for the identified message sent in downlink.

16.4.2.3 Traffic Efficiency Services

For the *Traffic Efficiency* class, two typical applications have been considered: XFCD and PDAS, which are applications that periodically request context-dependent information from a service provider. Both applications represent simple *one-way* uplink and downlink TCP/IP web-services, respectively [50], and are triggered in fixed periods of $t_{\text{request}}^{\text{XFCD}} = 300$ s and $t_{\text{request}}^{\text{PDAS}} = 60$ s, respectively.

16.4.3 Radio Access Network Performance Analysis

Focus has been set on three different key performance indicators (KPIs): application-specific one-way transmission delay (δ_{RAN}) and application-specific packet discard rate. The interpretation of the results of these two KPIs is supported by a third KPI, the uplink and downlink cell load.

In the first step the results of the system-level simulations are presented that have been conducted to evaluate the performance of the E-UTRAN [the RAN part in (16.1)].

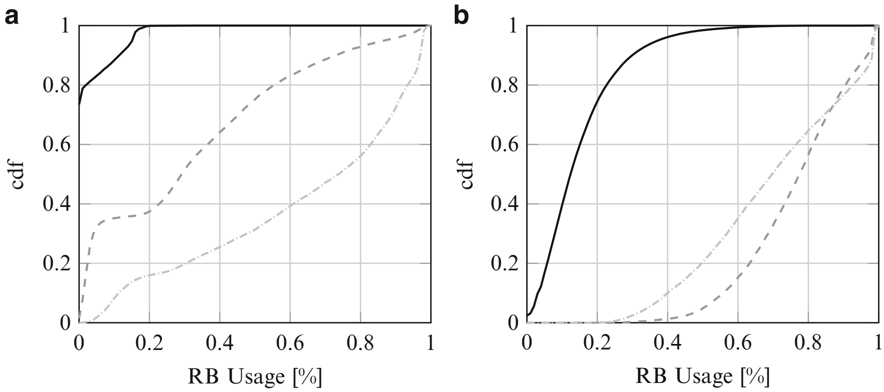

Fig. 16.4 RB usage in time for uplink and downlink data transmissions; urban (——), rural (- - -), highway (-·-·-). (**a**) Uplink. (**b**) Downlink

16.4.3.1 Network Load

The number of allocated RBs is an indicator for the load situation within the E-UTRAN. The term RB is used for the smallest scheduling unit of 1 ms interval and 180 kHz bandwidth in the time/frequency domain. Figure 16.4 shows the cumulative distribution functions (cdfs) of the percentage of allocated RBs in uplink and downlink for all TTIs in the different scenarios, respectively. Please note that the statistics involve all deployed services and terminal classes for all scenarios introduced in Sects. 16.4.1.2 and 16.4.2, respectively. They also include the traffic that is generated from the base load. In the *urban* scenario the 95th percentile shows an allocation of only 15 % of the available uplink and 37 % of the downlink resources. This means that in 95 % of the time not more than 15 % and 37 %, respectively, of the available RBs have been occupied. The network load is thus very low in this scenario. However, for the *rural* and *highway* scenario the cells are heavily loaded, which leads to occasional network congestion situations. The 95th percentile RB allocations show a downlink occupation ratio of 99 % in the *highway* and *rural* scenario. In uplink, the 95th percentile RB allocations are 87 % in the *rural* and 98 % in the *highway* scenario. Note that the average number of allocated uplink RBs in the *highway* scenario equals 65 % compared to the *rural* scenario with 33 %. However, in downlink on average more RBs have been assigned in the *rural* scenario (77 %) compared to the *highway* scenario (70 %). It can be concluded that the *urban* scenario represents a low-load scenario, whereas both, the *rural* and *highway* scenario, represent high-load scenarios. The reason for the different load situations is due to the diverse density of terminals within the cells. Because of the larger cell sizes in the *rural* and *highway* scenario, the total number of vehicles and

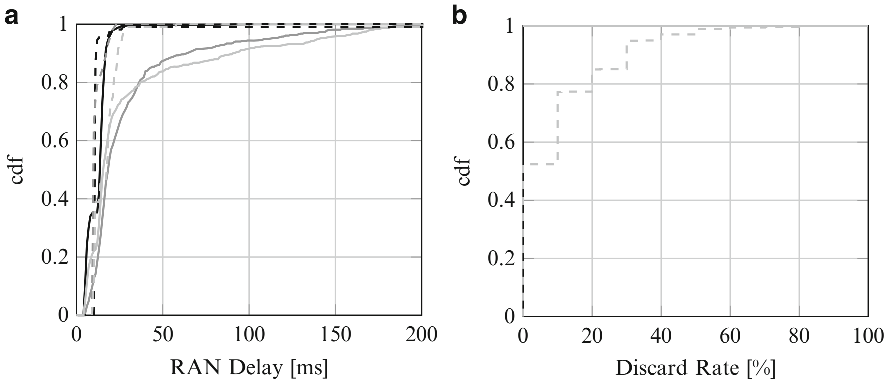

Fig. 16.5 RAN results for XFCD and PDAS; urban PDAS (——), urban XFCD (- - -), rural PDAS (——), rural XFCD (- - -), highway PDAS (——), highway XFCD (- - -). (**a**) Transmission delay. (**b**) Discard rate

mobile terminals is significantly higher than in the urban scenario. In consequence, network planning has to be adjusted to handle the high traffic demand. All in all, the selected scenarios represent examples for low and high load situations.

16.4.3.2 Delay and Packet Discard Rate Statistics

In the following, the cdfs of the delay and discard rate of packets in the radio access network (E-UTRAN) for services of the classes *Traffic Efficiency*, *Comfort*, and *Infotainment* are evaluated.

Traffic Efficiency Services The E-UTRAN delay (cf. δ_{RAN} in (16.1)) and discard rate results for the two automotive off-board services XFCD and PDAS are shown in Fig. 16.5, respectively. In the *urban* scenario the 95th percentile RAN delay is equally small for both services, i.e., 15 ms for XFCD and 19 ms for PDAS, and no packets have been discarded. For the *rural* and *highway* scenarios, the delays for XFCD and PDAS increase significantly. The 95th percentile RAN delay for PDAS in downlink is 146 ms in the *highway* scenario and 100 ms in the *rural* scenario. For the uplink service XFCD, the 95th percentile transmission delay is below 30 ms for all three scenarios. However, as a result of poor radio channel conditions and occasional network congestions in the *highway* scenario, significant amounts of XFCD packets have been discarded, with a 95th percentile discard rate of 40 %, cf. Fig. 16.5b. This indicates that the scheduler has not been able to allocate enough resources within the corresponding packet delay budget of 300 ms under the prevailing conditions of this scenario.

Comfort Services The QoS performance of the voice recognition service for the E-UTRAN part is shown in Fig. 16.6. For downlink transmissions the 95th

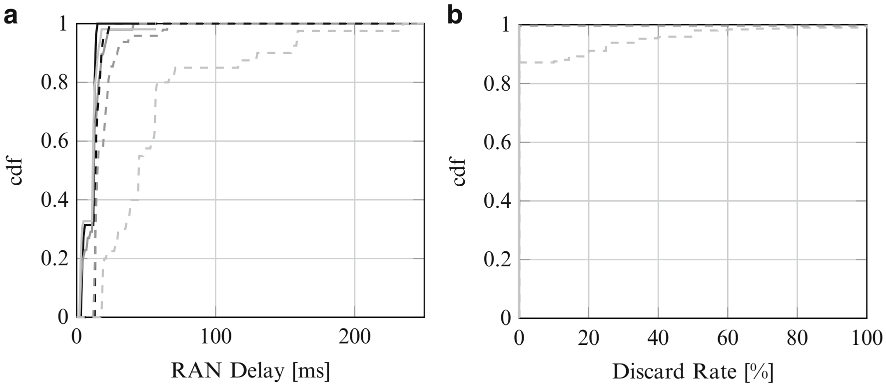

Fig. 16.6 RAN results for voice recognition; urban downlink (——), urban uplink (- - -), rural downlink (——), rural uplink (- - -), highway downlink (——), highway uplink (- - -). (**a**) Transmission delay. (**b**) Discard rate

percentile delay is around 25 ms in all scenarios, which can be explained by the small packet size. In only 5 % of the measurements, a delay higher than 25 ms has been observed. The 95th percentile uplink transmission delays are much higher in the *highway* scenario (i.e., 184 ms) compared to a delay of 52 ms in the *rural* and 20 ms in the *urban* scenario. Again, this can be attributed to the high network load and the poor radio channel conditions, which leads to packet loss, retransmissions, and discards. In the *highway* scenario the 95th percentile discard rate of uplink VR packets is 33 %, i.e., packets have not been scheduled in time and have been discarded (cf. Fig. 16.6b).

Infotainment Services The results of the video surveillance application are shown in Fig. 16.7. The cdfs show the statistics of both bearers jointly, i.e. the GBR and non-GBR bearer. In the *urban* scenario, the 95th percentile E-UTRAN delay is well below 80 ms. Nevertheless, the 95th percentile VS packet discard rate is 6 % (i.e., packets from the non-GBR bearer). In the *rural* and *highway* scenario a serious performance degradation has been observed with a 95th percentile transmission delay of 422 ms (cf. the *highway* scenario in Fig. 16.7a) as well as significant packet discards for both bearers. The 95th percentile discard rate is 50 % in the *highway* scenario and 94 % in the *rural* scenario. Yet, the 90th percentile for the *rural* scenario is below 20 %. Therefore, the average QoS performance for the VS application is much more degraded in the *highway* scenario with a mean discard rate of 42 % as opposed to the *rural* environment with 13 %. Since even packets from the GBR bearer get discarded occasionally, the VS application is rendered unreliable in these high-load scenarios.

Note that these results are related to the assumed high inter-site distance of 25 km in the *highway* scenario. The requirement from this analysis is a denser network deployment to provide more resources for the given number of users. It is more an issue of network optimization rather than a technology driven weakness.

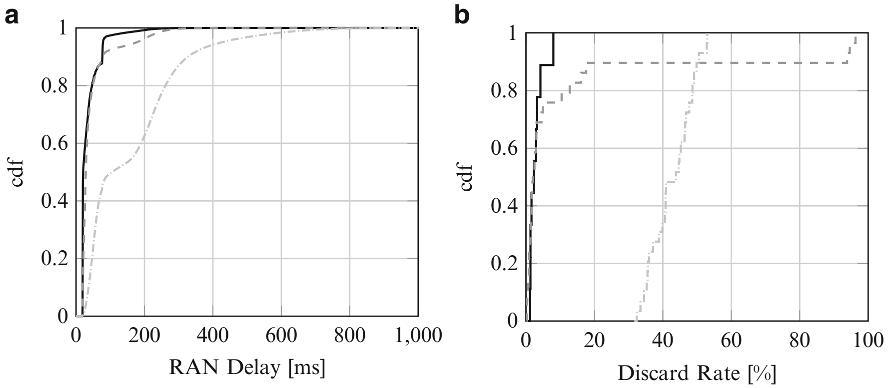

Fig. 16.7 RAN results for video surveillance; urban (——), rural (- - -), highway (-·-·-). (**a**) Transmission delay. (**b**) Discard rate

The cdf of transmission times for the FTP service (Fig. 16.8a) shows 95th percentile transfer times of more than 25 s for the *highway* and *rural* scenario. For the interpretation of this figure, the various simulated data volumes of up to 42 Mbit have to be considered. Under good radio channel conditions in a low load situation this data volume can be transmitted within a short time. An important aspect is how radio resource management (RRM) handles services with different priorities in a high load situation. The high transmission times for FTP can be attributed to the low QoS settings for this service and, hence, to its low scheduling priority.

Figure 16.8b shows the E-UTRAN transmission delays for the VoLTE service. In all three scenarios for uplink and downlink the 95th percentile delay remains below 20 ms. The step-wise nature of the cdf with a step-width of about 8 ms is due to occasional hybrid automatic repeat request (HARQ) retransmissions (cf. [34]). No packets have been discarded for both services. For VoLTE this is due to the strict QoS requirements and high scheduling priority, while in the case of FTP this is related to a large packet delay budget of 60 s (see Table 16.5).

For validation of the simulations, the results have been compared with real LTE network measurements presented in [41]. The one-way radio access network delay measurements presented in that work have been performed with packet sizes between 10 and 5,000 bytes in a live network under low traffic load conditions. When comparing the real network measurements with the simulation results of the low-load *urban* scenario, the 95th percentile delays are almost identical. In uplink the delay measured in [41] is 14 ms and almost equals the calculated delay in the simulations of 13 ms. In downlink a delay of 35 ms has been measured in [41], whereas a delay of 31 ms has been calculated from simulations.

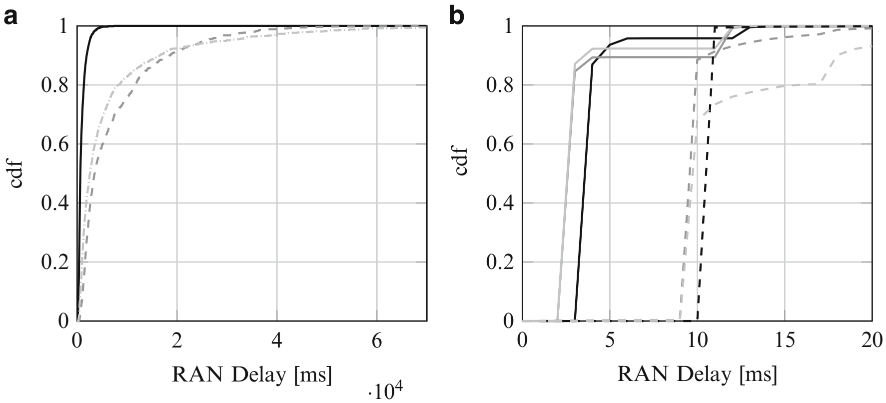

Fig. 16.8 RAN transmission delays for mobile terminal applications: FTP [urban (——), rural (– – –), highway (– · – · –)], VoLTE [urban downlink (——), rural downlink (——), highway downlink (——), urban uplink (– – –), rural uplink (– – –), highway uplink (– – –)]. (**a**) FTP transmission delay. (**b**) VoLTE transmission delay

16.4.4 Delay Analysis

Core Network Delay Analysis As defined in (16.1), the overall LTE transmission chain consists of the E-UTRAN delay as well as the core network (or EPC) and terminal (UE) delays. The EPC one-way delay (denoted as δ_{EPC} in (16.1)) in the user-plane is defined as the propagation time of a packet between the eNodeB and the PDN-GW. As estimated by 3GPP (cf. [6]), the overall core network delay, which depends on the virtual distance between the E-UTRAN and PDN-GW, can be assumed to take values between 10 ms and 50 ms. In the typical case that the radio E-UTRAN and the PDN-GW belong to the same public land mobile network (PLMN), the connection between them is fast and, thus, the average delay is around 20 ms. However, in a roaming scenario, the data packets will be routed from the foreign RAN to the home PDN-GW. In the case of large-distance communications (e.g., between the USA and Europe), the EPC delay might be 50 ms. Taking into account that the roaming case is less likely for the simulated scenarios, an EPC delay of $\delta_{\mathrm{EPC}} = 20$ ms has been assumed.

Terminal Processing Delay Analysis Eight categories for LTE terminals are defined in [10], where each category represents different capabilities. Among others, the number of spatial multiplexing layers, modulation sizes, buffer sizes, and supported peak data rates drive the complexity and costs of the required signal processing algorithms. The results of an extensive measurement campaign in [55] show that processing time at the terminal contributes to the E2E delay with 1.5 to 5 ms [cf. δ_{UE} in (16.1)].

Further Delay Aspects Besides the E-UTRAN and EPC transmission delays, further delays corresponding to mobility management processes have to be taken into account. In [7], the handover (HO) interruption time has been estimated by 3GPP as 15–25 ms for the uplink and 13–23 ms for the downlink. During this period, no data can be sent on the respective links. However, given such short interruption times, the scheduler tries to compensate for the lost time by favoring the affected packets. In this way, the QoS requirements will be fulfilled in most cases. Furthermore, only a few packets will suffer from the HO process. In the case of network deployments with small cell sizes (i.e., the *urban* scenario), it can be calculated that a vehicle terminal potentially has to perform one HO every 10 s. Based on this assumption, 1.2 packets/h in the case of PDAS are estimated to be affected, which is almost negligible. It should also be noted that in the unlikely event of a HO failure, an additional delay of up to 130 ms has to be taken into account. Note that in this work, no additional delay due to HOs or HO failures has been considered.

Further delays can arise at the initiation phase of a bearer, if the terminal has to perform idle-to-active state transition. According to [7], this process requires 61–115.5 ms. However, in this investigation, it is assumed that the vehicle terminals are always residing in connected mode in order to support premium connectivity for the automotive services.

Depending on the network operator's policies as well as on the terminal capabilities, an additional delay caused by discontinuous reception (DRX) also needs to be considered [34]. Different DRX cycles have been specified by 3GPP ranging from 0 to 2.56 s. The main goal of DRX is to increase the limited battery life time of mobile devices. Since battery life time does not pose a problem for vehicular terminals, the DRX mode has been disabled and, thus, does not need to be considered in the E2E delays for automotive services. From a network point of view, discontinuous transmission (DTX) provides the benefit of reducing interference in the network, which is of particular importance considering the fact that typical LTE deployments have a frequency reuse of 1.

16.4.5 Performance Discussion

In the following an overview of the overall perceived QoS performance is provided based on the one-way-delay of the total LTE (EPS) transmission chain, as defined in (16.1). The following assumptions have been made: $\delta_{\mathrm{UE}} = 5\,\mathrm{ms}$ and $\delta_{\mathrm{EPC}} = 20\,\mathrm{ms}$.

16.4.5.1 Infotainment Services

Requirements for the VS service have only been met in the *urban* scenario with a 95th percentile $\delta_{\mathrm{LTE}}^{\mathrm{VS}} = 105\,\mathrm{ms}$, which leaves room for additional delays such as for handovers. However, in the *rural* and *highway* scenarios the observed

E-UTRAN 95th percentile delay of 422 ms already exceeds the packet delay budget significantly. Furthermore, the 95th percentile discard rate of all VS packets is 94 % rendering this application highly unreliable in high-load environments. Note that this applies for both bearers, i.e., the GBR and non-GBR bearer. As a result, it is not feasible to deploy high-demand video streaming services in high-load scenarios with insufficient network capacity. However, a bearer based on a buffered-streaming service with QCI 6, as stated by 3GPP in [6], might be an appropriate choice for off-board video surveillance based services. Note that in high-load conditions QoS strategies can only be efficiently operated if a mix of services of different priorities is simultaneously served, i.e., also services of lower QoS priority have to be available that can be temporarily downgraded.

16.4.5.2 Traffic Efficiency Services

In the *rural* scenario, PDAS shows a 95th percentile delay of $\delta_{\text{LTE}}^{\text{PDAS}} = 205\,\text{ms}$, where $\delta_{\text{RAN}}^{\text{PDAS}} = 180\,\text{ms}$, $\delta_{\text{UE}} = 5\,\text{ms}$, and $\delta_{\text{EPC}} = 20\,\text{ms}$. Since this value is well below the delay budget (300 ms), even packets that suffer from additional handover or idle-to-active transition delays (which have not been considered in this work) would be delivered in time. In the uplink, XFCD shows even better delay behavior in the *urban* and *rural* scenarios with total LTE transmission delays below 55 ms. However, in the *highway* scenario, the bad channel conditions and corresponding high network load show 95th percentile packet discard rates of 40 %, which indicates that the quality expectations in such an environment are not fulfilled for the assumed network layout. The requirement is a denser network deployment to increase capacity.

16.4.5.3 Comfort Services

The performance of the VR service is similar to that of *Traffic Efficiency* services. In downlink, a 95th percentile delay of $\delta_{\text{LTE}}^{\text{VR,DL}} = 50\,\text{ms}$ has been calculated and almost no packets have been discarded. Uplink transmissions show a 95th percentile delay of $\delta_{\text{LTE}}^{\text{VR,UL}} = 209\,\text{ms}$. However, in the *highway* scenario again a non-negligible amount of packets has been discarded (i.e., a 95th percentile discard rate of 33 %) and, thus, the quality expectations for this lower priority service have not been met. Overall, in order to improve the perceived QoS for the TCP/IP-based web-services, especially for the uplink based VR transmission, the bearers should be deployed under QCI 6, rather than QCI 8 or 10. According to 3GPP this class is also defined for TCP/IP-based web-services with a packet delay budget of 300 ms but with a higher priority for scheduling, which in turn leads to a prioritized handling of the corresponding bearers compared to QCI 8 or 10.

The QoS requirements for the mobile terminal services (FTP and VoLTE) can be met. The VoLTE service is based on QCI 1 with a delay budget of 100 ms. In the uplink and downlink, the 95th percentile delay is $\delta_{\mathrm{LTE}}^{\mathrm{VoLTE}} \leq 45\,\mathrm{ms}$. This means that even additional delays due to handovers would not exceed the QoS delay budget.

16.5 LTE for Safety Services

In this section, the suitability of LTE to deliver messages of *Safety* applications is investigated. Features and requirements of *Safety* applications are presented and an overview of related work from standardization bodies and academia is given. Finally, a simulative analysis for CAM message distribution in a typical LTE deployment is presented.

16.5.1 Safety Applications: Features and Requirements

Safety applications require periodic V2V data exchanges in the neighborhood of a vehicle in the case of CAMs or event-triggered V2V and V2I communications in the case of DENMs. ETSI and International Organization for Standardization (ISO) are currently investigating the ability of LTE to support data exchanges for these cooperative applications. Preliminary results are reported in [24].

CAM and DENM exchanges in LTE involve transmissions from vehicles to infrastructure nodes and successive traffic distribution to the concerned vehicles. Unicast is always used for uplink transmission. In the uplink case, the problem is to select the most appropriate channel type without congestion risks. The random access channel (RACH) is a common uplink transport channel usually selected for signaling and to transmit small data amounts, such as CAM and DENM.

Unicast, multicast, and broadcast modes can be used on the downlink by leveraging eMBMS capabilities. Although eMBMS and its predecessor MBMS developed for UMTS deployments are not implemented in most current cellular networks, broadcast mode is more resource-efficient than unicast mode. Hence, it is strongly encouraged to use eMBMS for vehicular safety applications, although it could imply longer delays due to the eMBMS session setup.

ETSI specifications foresee the presence of a special-purpose backend server that supports geocasting, by intercepting CAM and DENM traffic from vehicles and processing it before redistributing it only to the concerned vehicles in a given geographical area [25]. In order to identify the concerned vehicles in a given area [42], the backend server has to know the list of geographic areas, their coordinates, and the position and IP addresses of all vehicles in any area at all times. According to the ETSI specifications [25], each time vehicles cross over to a new area, the server informs them about the coordinates of their current geographical area. The area size is application dependent, thus affecting the signaling load. Then data is distributed to the concerned vehicles through eMBMS or via multiple unicast connections.

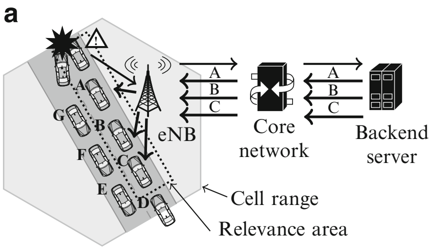

Fig. 16.9 DENM delivery in LTE. Only vehicles within the relevance area (*rectangular dotted area*) are addressed. (**a**) Unicast. (**b**) Multicast

The structure of the network deployment and location of the backend servers has an impact on the signaling procedures and latencies, as discussed in [42]. To reduce latencies in the centralized LTE architecture, the utilization of a combination of cloud-based servers and the LTE network has been proposed in [37]. In this study servers are located at different network locations between the edge of the network, i.e., network locations close to the eNodeB, and the Internet. The results show that the delay of the messages can be reduced, as the backend server moves closer to the eNodeB. If the server is installed in the mobile operator's core network, it may directly exchange location information with the MME module in the LTE architecture. This has the major advantage that the location information of the vehicles stored in the MME can be used for location-aware applications. Hence, no determination of the location through a separate process is required. In contrast, if the server is located in the Internet and thus decoupled from the mobile operator's network, each vehicle needs to maintain a connection to the server and send regularly position updates to it.

Figure 16.9 displays an example for DENM distribution procedures augmented with a backend server. In the case of unicast distribution, vehicles are addressed individually, so that the same message is separately transmitted to all concerned vehicles. In the multicast case, all vehicles in the relevance area are collectively addressed through geo-addressing capabilities leveraging the geographical position of terminals and a message transmission is performed using eMBMS (cf. Fig. 16.9b). In both cases, the latency of the message transmission might become critical, especially for localized safety-critical V2V communications.

Even for the distribution of CAM, messages have to cross the infrastructure for multicast distribution. In Fig. 16.10 the backend server collectively addresses all vehicles in the awareness range of the sending vehicles (A and B). In contrast Fig. 16.11 shows the situation when an IEEE 802.11p network is available. A single broadcast transmission can be used to distribute the message from a vehicle in its awareness range (in the case of CAMs) or within the relevance area in the case of DENMs.

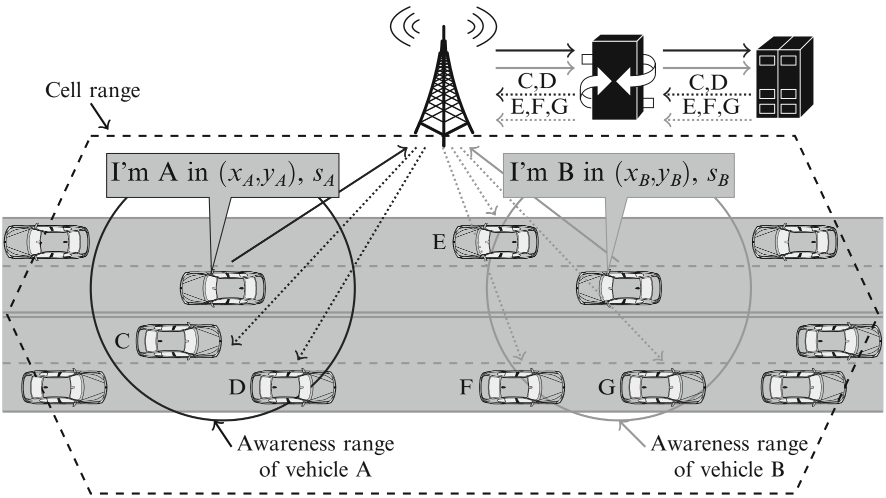

Fig. 16.10 Multicast CAM delivery. The awareness range of the vehicles does not coincide with the cell range (adapted from [16])

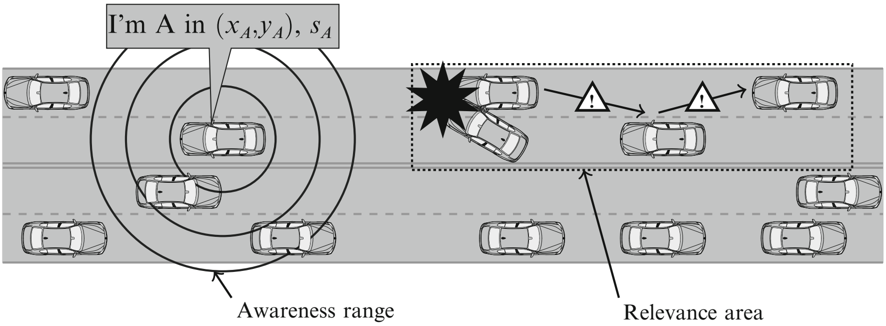

Fig. 16.11 CAM and DENM delivery in IEEE 802.11p. Messages are locally broadcasted through V2V communications (adapted from [16])

16.5.1.1 CAM Support over LTE

In addition to the outcomes of standardization bodies, the support of vehicular safety applications through LTE has been investigated in recent literature. Analytical results in [61] show that LTE is unable to satisfy the CAM delivery requirements if the eNodeB retransmits all received CAMs to every vehicle in the cell using unicast transmissions. Similar results are achieved if the eNodeB unicasts aggregated CAMs to every vehicle in the one-hop neighborhood. Improvements can be obtained through CAM broadcasting in the cell.

In [51] the authors enhance the unicast CAM downlink transport with a filtering scheme in order to reduce the load in the cells and to meet the CAM delay requirements. Filtering relies on the idea that not all vehicles in a cell need to receive all CAMs. Accordingly, based on the received vehicle's location information, the backend server selects a subset of vehicles that receive CAMs on unicast links. Results attained in urban and rural scenarios show that the selective unicast of aggregated CAMs might also overload the LTE network. A higher number of vehicles per cell can be served when decreasing the CAM rate down to 2 packets/s, instead of 10 packets/s. The conducted study has contributed to the architecture and the results reported in [25]. The authors in [25] suggest to use the eMBMS to increase the downlink capacity. Additionally, the authors of [46] advocate the complementary use of cellular systems and IEEE 802.11p to successively broadcast the received CAMs on the downlink at road intersections, where IEEE 802.11p may suffer from non-line-of-sight conditions due to the shadowing effects caused by buildings.

The impact of the remote server position on the overall performance is investigated in [38] for both eMBMS and non-eMBMS architectures. The results of the investigation using eMBMS show that up to hundrets of vehicles within each cell can be supported. Furthermore, simulation results indicate that locating the server at the edge of the network close to the vehicles reduces both the end-to-end latency and the RAN network traffic by requiring less frequent updates to achieve the intended freshness of information. The remote server plays an active role in reducing the network load, while keeping the information as fresh as possible, in the solution proposed in [63]. There, the authors suggest the server to coordinate transmissions from and to vehicles to determine an optimum transmission rate based on network observations. Such observations can be acquired at the application layer. The delay and transmission rate of the latest packet, for instance, are among the considered performance indicators. The suggested rate is transmitted in already exchanged CAM and DENM packets, without incurring additional signaling overhead.

Besides the influence of the architecture, the applied scheduling techniques in the eNodeB have a major impact on the transmission of CAM messages. In [57] it is assumed that CAM messages offer similar traffic patterns as VoLTE traffic. This is because they both foresee the frequent transmission of small-sized packets with a short information relevance. In [57] three different scheduling techniques proposed for VoLTE are discussed. First, dynamic scheduling is presented, where the UE sends a resource request message to the eNodeB for every data packet. Second, using persistent scheduling a dedicated amount of resources is statically reserved for the time of the data transmission. Third, semi-persistent scheduling applies persistent scheduling for initial transmission and dynamic scheduling for retransmissions. All schemes have their advantages and disadvantages for the CAM message distribution. Persistent and semi-persistent scheduling well match the requirements of a fixed beaconing rate, e.g., a CAM per vehicle at every 100 ms. Dynamic scheduling, on the other hand, is capable of handling adaptive beaconing schemes, where the transmission of CAMs may vary, e.g., according to the vehicle speed. The proposed solution foresees that the UE sends a scheduling request via random access for initial connection setup, then the eNodeB schedules resource blocks for subsequent CAMs. When a vehicle stops because of a red light, it stops sending CAMs and frees resources that the eNodeB can reuse.

The study in [58] has been conducted in the same scenario with the focus on a priority-based congestion control algorithm for improving CAM delivery at intersections. The eNodeB receiving CAMs is able to identify potential collision patterns and is able to send back warning messages to vehicles. No interference from other traffic is considered, since a dedicated 700 MHz Public Safety Band allocated in the USA by the Federal Communications Commission (FCC) for broadband communications is assumed to be used. However, so far it has not yet been decided how much bandwidth should be assigned for intersection assistance applications. Each user is given a priority when the bandwidth threshold is reached and low priority users (i.e., the ones further apart from the intersection) are removed to reduce the cell load.

To reduce load on the cellular network, when targeting CAM delivery at intersections, a hybrid approach is proposed in [59] that leverages both Wi-Fi and LTE technologies. According to the described solution, when a vehicle approaches an intersection, it first broadcasts beacons through its Wi-Fi interface to form a cluster. The cluster head is then responsible for sending CAMs to the base station, that, in turn, forwards CAMs to cluster heads in other road segments to keep them informed. The cluster heads forward the message sent by the base station via Wi-Fi to the cluster members. Results show that the clustering scheme significantly improves the CAMs delivery performance with respect to schemes relying on LTE and Wi-Fi only, while reducing the network load. On the other hand, the delay increases compared to a Wi-Fi only scheme where direct communications can be enforced between vehicles. In the hybrid approaches, different delay contributions should be considered, ranging from the transmission of CAMs over LTE, the processing at the eNodeB and at upper LTE layers, the identification of the set of receivers, their downlink scheduling and their forwarding from the eNodeB to other cluster heads. Overall, the delay values are below 100 ms, hence matching the application demands.

The main assumption in the above-mentioned studies is that the LTE capacity is exclusively used for CAMs, without accounting for other vehicular and non-vehicular traffic with different QoS requirements, which significantly affects performance.

16.5.1.2 DENM Support over LTE

DENMs generated as a reaction to a hazard have a limited lifetime and the number of senders is typically significantly lower compared to CAMs. Hence, DENMs generate a lower traffic load compared to CAMs.

The main challenge is related to simultaneous warning transmission attempts by all vehicles detecting a specific hazard. For example, in case of slippery roads, vehicle collision events may be detected and notified by every vehicle passing the area. In this case, the backend server plays the crucial role of a reflector and aggregator. It can filter the multiple uplink notifications of the event according to the location, time stamp, and heading field of the received messages to send only one consolidated message [24]. The latter feature allows the server to infer a better general view of the road conditions [28]. In addition, the detecting vehicle receives an implicit acknowledged notification of the same event on downlink. It has no need to repeat the same DENM transmission several times. System scalability is thus improved, channel resources are saved, and uplink congestion is avoided. As an additional benefit, the wide cellular coverage guarantees the event dissemination also when there is no nearby vehicle to relay the message, which would hinder propagation of messages when 802.11p is used instead. Therefore, DENM over LTE results in a much more reliable solution as demonstrated in [24, 51] for a system where no background load was assumed. In [40] the traffic is generated from a single vehicle transmitting a DENM to the base station, which repeatedly rebroadcasts it to all vehicles in the cell through MBMS. Different downlink scheduling schemes are compared, showing that QoS-aware schemes meet the DENM delay constraints.

16.5.2 Performance Evaluation

In this section, the delivery performance of CAMs generated by vehicles is evaluated through simulations, under different network and load conditions.

16.5.2.1 Simulation Settings and Assumptions

Simulations have been conducted using ns-3 [56] with the LENA (LTE-EPC Network Simulator) extension [44] to model the E-UTRAN and the core network modules (S-GW, PDN-GW, MME).

SUMO (Simulation of Urban Mobility) [54] is used to generate the road topology and the mobility patterns of vehicles that move over a regular 4×4 grid road topology where each road segment is 250 m long. The eNodeB is installed in the center of the road topology. Focus has been set on the scenario with one eNodeB for simulation efficiency considerations. Vehicles send CAMs to a remote server, which forwards the CAMs towards vehicles in the awareness range in downlink direction. A dedicated link is assumed for the connection between the PDN-GW and the server. To this end, the delay between the PDN-GW and the remote server (δ_{PDN}) is set to 0 ms. For the simulations, $\delta_{\mathrm{OFF\text{-}BOARD}}$ and $\delta_{\mathrm{ON\text{-}BOARD}}$ are also set to 0 ms.

To investigate the effect on the performance of safety messages, three traffic load cases have been analyzed. In *Case A*, only vehicles transmitting CAMs are considered in the cell. In *Case B*, fifty pedestrian users are added that generate interfering voice calls, which are mapped as VoLTE traffic and modeled with an ON/OFF Markov chain. During the ON period, the source sends 20 byte data packets every 20 ms (i.e., a source data rate of roughly 8 kbit/s). In *Case C*, the simulated interfering traffic is heavier; 40 of the 50 pedestrian users continue to generate voice calls while the remaining ten users generate video traffic with a source rate of roughly 128 kbit/s. In all three simulated cases, the number n of vehicles generating CAMs varies where $n \in \{50, 100, 150, 200\}$. Both distributed and simultaneous vehicle arrivals are considered in the three cases and separately analyzed in the following subsections.

The focus of the conducted simulations is set to the uplink direction (both data and control channels) to get quantitative insights into the LTE channel access procedure and the related congestion problem. The uplink is the more critical link of the two channel directions due to the congestion risks from massive data access. Moreover, data aggregation and geocasting (implemented through enhanced multicasting or broadcasting) can be used in downlink direction from the remote server to the intended set of receivers [51].

Similarly to [51], a round-robin MAC scheduler is used. Further LTE simulation settings are similar to the ones in [58] and are listed in Table 16.6. Focus is set on two KPIs for CAM transmissions: one-way transmission delay (δ_{RAN}), from the vehicle to the eNodeB, and packet delivery ratio. In addition, the throughput performance is computed for the interfering VoLTE and video traffic.

16.5.2.2 Scenarios with Distributed Vehicle Arrivals

The aim of the analysis reported in this subsection is to assess the suitability of LTE in supporting CAM traffic in typical scenarios (with and without interfering traffic) when several vehicles attempt to access the network at different time instants based on their mobility patterns. Specifically, a uniform vehicle arrival rate in the cell within a 2 s time interval is considered. After the arrival in the cell, each vehicle performs the random access procedure. When this procedure is successfully completed, it starts to send data. In *Cases B* and *C*, the interfering users are assumed to be already active in the cell at the start of the simulations. In all simulations, an LTE channel bandwidth of 5 MHz is considered.

The results displayed in Fig. 16.12 show the packet delivery ratio and one-way transmission delay for the three *Cases A, B*, and *C*. The amount of resources in the LTE system can ensure full reliability, i.e., CAM packet delivery ratio is 100 % in all the considered cases. In other words, the results highlight that the LTE random access procedure is able to manage the arrival of hundreds of vehicles if they have different arrival time instants. As shown in Fig. 16.12, the CAM transmission delay is 12 ms independent of the number of vehicles in the cell and in all of the simulated Cases. This demonstrates that LTE is able to meet the time-constraint of CAM messages.[2]

[2]The delay in downlink direction is expected to be comparable with or even shorter than 12 ms, hence leading to an overall delay below 100 ms.

Table 16.6 Main simulation settings

Parameter	Value
Simulated Area	1 km × 1 km
Layout	Grid topology
Road segment length	250 m
Speed limit	50 km/h
Frequency band	2 GHz
TTI	1 ms
DL Tx Power	40 dBm, antenna gain 14 dBi, Noise figure 5 dB
UL Tx Power	20 dBm, antenna gain 0 dBi, Noise figure 9 dB
System bandwidth	5 MHz, 10 MHz (25 RB, 50 RB)
RB size	12 sub-carriers, 0.5 ms
Sub-carrier spacing	15 kHz
Data/control OFDM symbols	11/3
Scheduling algorithm	Round Robin
CAM packet size	100 Byte
CAM frequency	10 Hz
CAM QCI	8
Interfering VoLTE QCI	1
Interfering video QCI	7
Propagation model	Friis
Thermal noise	−174 dBm/Hz
Simulated time	100 s

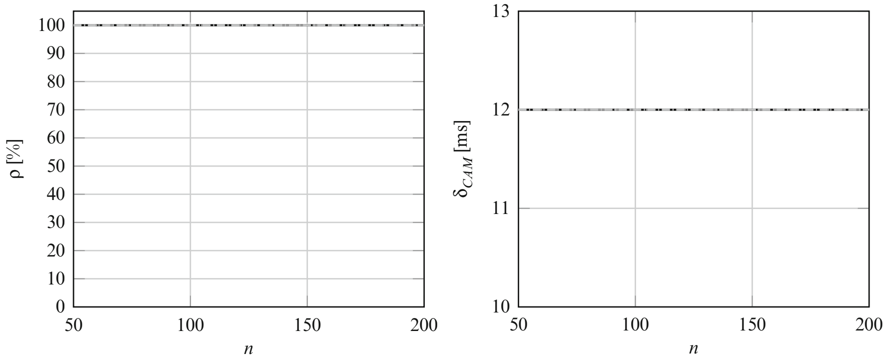

Fig. 16.12 Distributed vehicle arrivals: CAM packet delivery ratio (ρ_{CAM}) and delay (δ_{CAM}) vs. the number of vehicles transmitting CAMs (n) in *Case A* (——), *B* (– – –), and *C* (– · – · –)

The throughput of VoLTE and video interfering traffic in *Cases B* and *C* is plotted in Fig. 16.13. In *Case B*, it can be observed that VoLTE users are not

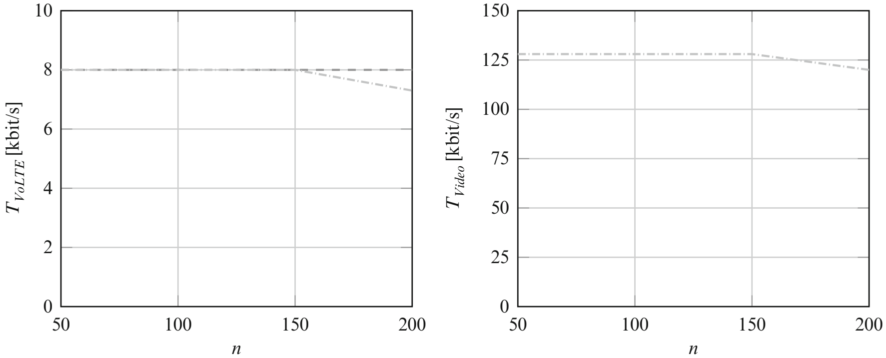

Fig. 16.13 Distributed vehicle arrivals: throughput of VoLTE (T_{VoLTE}) and video (T_{Video}) vs. number of vehicles transmitting CAMs (n) in *Case B* (- - -) and *C* (- · - · -)

influenced by the CAM transmission, i.e., the throughput is 8 kbit/s. Hence, LTE can simultaneously handle both CAM and VoLTE traffic without any performance degradation.

In *Case C* the mean throughput of VoLTE gradually decreases when more than 150 vehicles are in the cell and it goes down to a value of 7.6 kbit/s with 200 vehicles per cell. A similar trend can be noticed for video flows, which keep a mean throughput of 128 kbit/s when up to 150 vehicles are considered. Under the heavy load of 200 active vehicles in a cell, however, their mean throughput decreases to 120 kbit/s. Under these assumptions, LTE is able to support the arrival of up to 150 vehicles in few seconds per cell without significantly affecting the performance of other traffic (i.e., VoLTE and video). Indeed, the throughput of VoLTE and video traffic is reduced by 6 %, respectively, 5 % when a large number of vehicles (i.e., 200) is active in the cell.

16.5.2.3 Scenarios with Simultaneous Vehicle Arrivals

In this subsection, a worst-case scenario is considered when *all* vehicles in the cell perform the random access procedure *simultaneously*. After the random access accomplishment, CAM transmission attempts by vehicles are distributed within a 2 s time interval. The performance is evaluated under different network load and deployment settings in *Cases A*, *B*, and *C* for two bandwidths, i.e., 5 and 10 MHz. With 10 MHz bandwidth, a higher number of resources is available with respect to the 5 MHz case, with an expected positive impact on the performance of the random access procedure.

In Fig. 16.14 the CAM delivery ratio ρ_{CAM} is displayed for all three cases and both 5 and 10 MHz bandwidths. It can be observed that full reliability (i.e., $\rho_{\text{CAM}} = 100\,\%$) can be achieved *(i)* for 5 and 10 MHz channels in *Case A*, and *(ii)* for 10 MHz bandwidth also in *Case C*. In the other cases, full CAM reliability

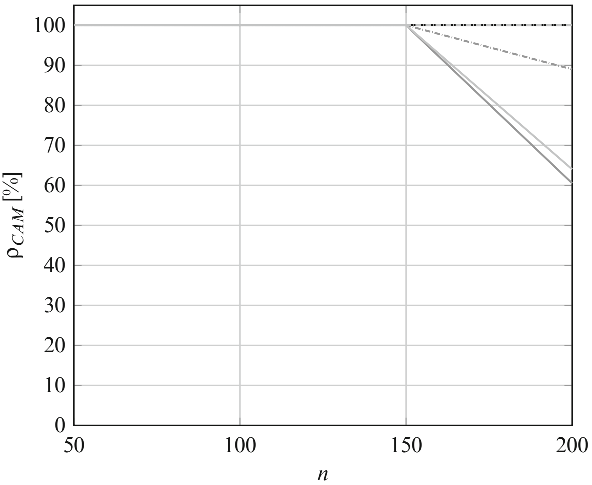

Fig. 16.14 Simultaneous vehicle arrivals: CAM packet delivery ratio (ρ_{CAM}) vs. number of vehicles transmitting CAMs in *Cases A*, *B* and *C* when varying the channel bandwidth. *Case A*: 5 MHz, 10 MHz (——); *Case B*: 5 MHz (——), 10 MHz (-·-·-); *Case C*: 5 MHz (——), 10 MHz (-·-·-)

is achieved for a number of vehicles up to $n = 150$. For a higher number of vehicles, packet delivery ratio decreases. This results from the limitations of the random access mechanism. As a very large number of vehicles (i.e., $n \geq 150$) tries to access the network simultaneously, only a portion of them is successful. Vehicles having access to the network experience a packet delivery ratio equal to 100 % with a delay almost equal to 12 ms, while the other vehicles are blocked at the access and consequently cannot transmit CAMs.

With 10 MHz bandwidth, the number of resources available in the uplink/downlink physical channels increases and this allows a larger number of vehicles to successfully access the network. As a result, the packet delivery ratio improves compared to the cases of 5 MHz bandwidth.

It is worth noticing that in *Case C* vehicles experience better performance than in *Case B*. This is due to the fact that in *Case B* there is a higher number of VoLTE connections that frequently transmit (i.e., every 20 ms) and compete with vehicles for resource assignment. In *Case C*, VoLTE flows are fewer and the additional video flows have higher periodicity (equal to 40 ms according to the simulation settings) compared to VoLTE. This improves the scheduling efficiency in eNodeB and thus the CAM delivery (Fig. 16.15).

Similarly to CAMs, the performance of VoLTE and video traffic also deteriorates as the number of vehicles transmitting CAMs exceeds 150. This effect is more evident in scenarios with 5 MHz bandwidth.

All in all, LTE is able to support CAM traffic ensuring full reliability and meeting delay constraints under low-to-medium vehicular load conditions. If the cell is

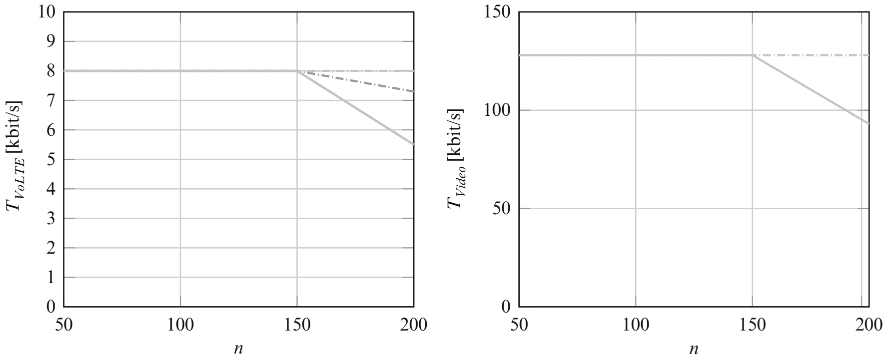

Fig. 16.15 Simultaneous vehicle arrivals: throughput of VoLTE (T_{VoLTE}) and video (T_{Video}) vs. number of vehicles transmitting CAMs (n) in *Case B* when varying the channel bandwidth. *Case B*: 5 MHz (——), 10 MHz (- · - · -); *Case C*: 5 MHz (——), 10 MHz (- · - · -)

highly congested, new workarounds both in the random access and scheduling techniques should be specifically conceived to meet the QoS requirements of vehicular safety applications and, at the same time, not penalize base load traffic.

16.5.3 Concluding Remarks

In this section, an overview about CAM and DENM message transmissions in LTE network deployments has been given. The following concluding remarks can be summarized:

- For DENMs, LTE can provide the ability (i) to consolidate the numerous event notifications originated from all the vehicles in a given area, and (ii) to disseminate only useful information in a specific area, with positive effects on system scalability, congestion avoidance, and delivery reliability.
- CAM delivery through LTE may suffer from poor uplink performance due to congestion under heavy load conditions. The simulated scenarios show performance degradations for a load of more than 150 vehicles per cell. However, LTE provides advantages in terms of coverage in specific hazardous areas such as road intersections, where obstacles like buildings can obstruct direct V2V communication.
- Unicast CAM delivery is less resource efficient than eMBMS delivery but it may show advantages in terms of delays, since multicast setup procedures can be avoided.
- The backend server plays a key role in V2V communications. The vehicle-to-server and in-network signaling load, which is also server-location-dependent, and the required intelligence at the server vary with the vehicular application. Besides reflecting or aggregating messages, the server may also take care of

repeating a message as long as the notified event persists so that information can be refreshed for newly arriving vehicles [28] in the relevant area. It can also regulate the transmission rate of CAMs and DENMs in response to network observations.

16.6 Comparison of 802.11p and LTE for Automotive Services

In the following the core features of LTE and IEEE 802.11p,[3] specifically conceived for vehicular environment, as potential wireless connectivity technologies for vehicular applications are compared and contrasted.

Coverage and Mobility LTE relies on a cellular deployment of eNodeBs offering a wide area coverage. This would solve the IEEE 802.11p issue of poor, intermittent, and short-range connectivity of approximately 300 m, and would particularly favor LTE for V2I communications even at high terminal speeds. The use of LTE for V2X communication also represents a viable solution to bridge the network fragmentation and extend the connectivity in those scenarios where direct V2V communications cannot be supported due to low car density (e.g., off-peak hours, rural scenarios, etc.) or due to challenging propagation conditions (e.g., corner effect due to buildings or obstructions at road intersections). Furthermore, the coverage of LTE can even be increased by incorporating other co-deployed cellular wireless technologies, such as UMTS. An inter-radio access technology handover is performed automatically by the core-network of the mobile network operator. The *centralized* nature of the cellular network has the following drawback compared to the 802.11p technology: it does not natively support direct V2V connectivity. Instead, messages require to be passed through infrastructure nodes in the core network.

Market Penetration and Transmission Costs A higher market penetration rate is expected to be achieved by LTE compared to IEEE 802.11p. This is an important aspect as ad hoc networks suffer from the typical chicken-and-egg deployment problem, since a certain penetration rate of IEEE 802.11p equipped vehicles is required before this can be considered an effective approach. An important aspect is that the LTE network interface is integrated in common user devices like smart phones and passengers are accustomed to being connected to the Internet through these devices while being on the road. A further meaningful difference between the two technologies is the cost and provider aspect. While IEEE 802.11p uses a dedicated transmission band for vehicular communication, which is free of charge and requires no further operator, the use of cellular communication systems always relies on mobile network operators, which charge for the use of the transmission system.

[3] See Chaps. 3 and 4 for a more detailed description of the IEEE 802.11p standard.

Capacity LTE offers high downlink and uplink capacity (up to 300 and 85 Mbit/s cell throughput, respectively, in 3GPP Rel. 8, and up to 1 Gbit/s for LTE-A in Rel. 11). Such values are much higher than the 27 Mbit/s offered by IEEE 802.11p. In case of further increasing throughput demands, additional capacity per area can be achieved by a denser LTE network deployment.

Latency Depending on the automotive service, the latency performance might have a significant influence on the application performance, especially for *Safety* services. Besides the transmission delays introduced by LTE in the E-UTRAN and the EPC [cf. Eq. (16.1)], the state mode of the mobile terminal has major impact on the overall latency. In order to save resources, cellular networks are configured to keep non-active terminals in idle mode. The transition from idle to connected state takes typically more than 50 ms, whereas within the connected mode, the transition from dormant to active state takes only around 10 ms. Therefore, it is recommended to keep vehicles that send periodic CAMs always in the connected mode. However, for the transmission of an event-triggered DENM, delays caused by state transitions from idle to connected mode are less critical.

Complementary Usage of 802.11p and Cellular Communication Systems ETSI, ISO Communications access for land mobiles (ISO CALM) and the Department of Transportation (DOT) are currently investigating the complementary roles of IEEE 802.11p, LTE, and other cellular technologies in supporting cooperative V2V and V2I applications [24, 37, 53]. In agreement with the ISO CALM guidelines, the ITS station reference architecture proposed in the ETSI specifications [25] leverages the complementary strengths of distributed short-range networks (e.g., IEEE 802.11p and its European counterpart ITS-G5, Wi-Fi) and centralized cellular technologies, among which LTE and its successor LTE-A are the most promising ones. Early indications of this trend toward heterogeneous networking in the complex vehicular environment can be found in the USA as well [53].

16.7 Open Challenges and Future Research Topics

The applicability of LTE for vehicular non-safety and safety services has been investigated in the previous sections. This evaluation shows that LTE is not able to strictly fulfill the stringent requirements for vehicular safety applications with its current settings and, therefore, requires further research and standardization efforts. This section provides an outlook to future cellular technologies such as LTE-A as well as the upcoming 5th generation (5G) wireless communication systems and highlights their applicability for future vehicular services.

16.7.1 Amendments in LTE-A

16.7.1.1 Features of LTE-A

The evolution of LTE, LTE-A, is designed to support even higher data rates, i.e., downlink rates of 1 Gbit/s for low mobility (100 Mbit/s for high mobility) and uplink rates of 500 Mbit/s. This is achieved by carrier aggregation to bandwidths of up to 100 MHz. In addition, enhanced MIMO techniques, relay nodes and an acceleration of the HARQ process have been introduced in LTE-A [32], which increases the overall capacity and reduces the delay in the radio access network significantly. The increased offered capacity reduces the transmission durations especially for high data volume transfers. It also reduces blocking and, thus, the waiting time until the start of the data transmission. In LTE-A delays are further reduced by configuration changes. The Physical Random Access Channel (PRACH) allows random access with a periodicity that can vary from 1 to 10 ms. Also the access for a scheduling request is reduced to 1 ms instead of 10 ms. Moreover, 3GPP is working on evolving LTE-A to accommodate the requirements of Machine Type Communication (MTC), that potentially involve a huge number of communication devices autonomously (i.e., without human intervention) exchanging small amounts of data traffic. Several vehicular applications, like FCD, vehicle diagnosis, and fleet management, that imply data collection from in-vehicle sensors and their transmission to a remote server, are considered for MTC in [5]. Solutions under study in 3GPP for efficient transmission of small amounts of data with minimal network impact (i.e., minimal impact on signaling load, network resources, delay, energy consumption) show promising performance [3, 4].

An important aspect for automotive applications is that LTE-A will be able to serve a higher number of users simultaneously at high quality, such as video streaming for infotainment applications. Moreover, the larger bandwidth will also provide enough network capacity for a temporary high number of CAMs to be served in parallel to the base traffic load. Although LTE-A promises latencies as low as 10 ms over the air interface, end-to-end latencies including propagation through the core network and data processing at a backend server in the cloud are expected to be in the order of several 100 ms.

16.7.1.2 Direct Device-to-Device Communication over Cellular Systems

A further reduction of latencies is expected from direct D2D communication [21]. The D2D communications paradigm enables two mobile devices in the proximity of each other to establish a direct local link and bypass the cellular infrastructure in the data plane. Among other benefits (see [29]), this leads to a hop gain referring to the usage of a single transmission link rather than two transmission links when exploiting both UL and DL resources in a conventional cellular system. Hence, the E2E delay can be reduced substantially, especially for safety applications requiring local data exchange between vehicles.

As a part of the studies conducted within the Rel. 12 activities, 3GPP has defined multiple work items considering D2D communication in cellular (i.e., LTE-A) networks [1]. In the first stage of the investigations, 3GPP focuses on a feasibility study [2] for proximity services (ProSe), i.e., services that rely on D2D communication. The objectives of this study include the investigation of use cases that benefit from the D2D paradigm and their requirements. The studies are focused on mechanisms for network-assisted device and service discovery that enable services like social networking, local advertising, or public safety applications [2]. As an example for automotive applications, 3GPP defines a use case for a parking spot finding assistant at high user density. However, none of the described use cases hint at ProSe support for two of the most important aspects of vehicular communications: high mobility[4] and strict latency requirements. Multi-operator support (i.e., enabling D2D communications between subscribers of different PLMNs) is the third major hurdle towards the realization of V2X services based on the D2D communications paradigm. This challenge is being addressed by 3GPP as it is common to virtually all of the ProSe use cases considered in [2]. While further effort on normative work regarding ProSe and a solution enabling multi-operator support should be expected from 3GPP, it remains questionable whether support for high mobility and E2E delay constraints will be part of the refinements in LTE-A. Therefore, automotive applications (or at least those with strict QoS requirements) based on the D2D communications paradigm might prove to be infeasible before the introduction of 5G wireless communication networks.

An early discussion about the usage of D2D for vehicular applications can be found in [31]. A preliminary solution leveraging D2D for broadcast dissemination of CAMs is proposed in [39].

16.7.2 Future 5G Communication Systems

To meet the expectations of the 2020 wireless communications society, future 5G mobile communication systems have to be significantly more efficient and scalable in terms of energy, costs, and spectral efficiency. Currently, several projects and initiatives investigate the requirements of 5G wireless systems [26, 27]. The technical goals highlighted in the European Union 5G flagship project METIS[5] are

- 1,000 times higher mobile data volume per area
- 10–100 times higher number of connected devices
- 10–100 times higher typical user data rate

[4]It should be noted that mobility has been brought up for a discussion within the 3GPP as a part of the feasibility study [12, 13], but a corresponding contribution was not adopted in the final report.

[5]*M*obile Communications *E*nablers for the *T*wenty-twenty (2020) *I*nformation *S*ociety.

- 10 times longer battery life for low power massive machine communications, and
- 5 times reduced End-to-End latency,

with similar cost and energy consumption as today's networks. Moreover, it is commonly agreed that in comparison with current legacy systems future 5G systems need to be flexible enough to support a significant diversity of applications and use cases implying different service requirements in terms of reliability, availability, and latency that current wireless communication systems typically are not able to guarantee. For example, road safety systems require very low latencies in the order of ms and high reliability (i.e., high probability of error-free packet delivery within a fixed latency deadline) even under poor radio channel conditions.

5G as Enabler for Vehicle-to-device (V2D) Communications V2X communication is currently discussed as a potential service that could be enabled by future 5G networks [27]. The potential benefit of integrating V2X communications in a future 5G communication system lies in the high market penetration, which allows to overcome the chicken-and-egg deployment problem of 802.11p based systems (referred to in Sect. 16.6). By enabling V2X communication capabilities in cellular modems, not only information between vehicles as well as between vehicles and road side units could be exchanged for safety purposes, but also between vehicles and communication devices of vulnerable road users (VRU), such as pedestrians and cyclists. This so-called V2D allows for reaching a very powerful sensor that already today almost everyone carries in his pocket: a mobile device (such as a smartphone or a tablet). In such a way, safety-relevant information can be collected directly from the VRU's devices in order to actively initiate the necessary actions for avoiding accidents. In this sense, the electronic horizon of vehicles will be significantly extended to all traffic participants. Thus, D2D communication is instrumental for the implementation of V2D safety services. However, in order to cope with their requirements, smart resource allocation and interference management schemes [17] are needed. Considering the high velocities that can be expected with V2X communication, one of the biggest challenges in this regard is the collection of reliable channel state information with a minimum amount of signaling. In addition, ultra-fast device and service discovery schemes are required. Moreover, the use of both network-controlled and pure ad-hoc (i.e., without network control) D2D communication needs to be supported in a smart and complementary manner in order to enable the exchange of information between traffic participants even in locations with insufficient network coverage. In this way, the availability of V2X safety services can be increased significantly. Finally, spectrum demand and management options for V2X communications in 5G networks require further analyses and standardization in order to provide multi-operator support among D2D/V2X devices.

5G as Enabler for Real-time Off-Board Applications The evolution of remote services allows not only the storage of data on a common entity, e.g., a server in the Internet, but also the remote execution of applications, e.g., office applications. This means that a mobile terminal can shift certain complex processing tasks to a remote server, whereas the terminal itself only serves as a user interface and therefore can relieve its own local processing units. The automotive and transportation industry will rely on remote processing to ease vehicle maintenance and to offer novel services to customers with very short time-to-market cycles. Moreover, the real-time aggregation of vehicle environment data can be used to realize an extended electronic horizon for vehicles, which can serve as an enabler for next-generation highly automated driving. The challenge to realize these services, especially when considering terminals that move at high speeds, lies not only in the provision of high data rate communication links for mobile terminals, but also in the fact that these services require low latencies and reliable transmissions. The former can be achieved by using novel waveforms, advanced modulation and coding schemes, and further diversity exploitation. These techniques enable high mobility robustness and reduced coding/decoding latency while ultra-reliable communications will ensure the reliability and availability of such services. Advanced handover optimization mechanisms [52] allow for seamless connectivity and, hence, also contribute towards the fulfillment of real-time requirements. Moreover, the utilization of context information (such as trajectory prediction) can be used as a basis for seamless content delivery and QoS control [14]. Last but not least, future 5G networks have to cope with a number of devices that is 10–100 times higher compared to a basis system of today, e.g., 3GPP LTE Rel. 11. In order to achieve this, the signaling overhead needs to be minimized.

This section has given an outlook to current and future research fields. Since new technologies are not suddenly deployed, a smooth evolution from services that can be operated in today's wireless communication networks towards more sophisticated services based on future 5G technologies is expected. On the one hand, 5G communication technologies will provide the basis for developing a huge variety of new applications, e.g., delay sensitive services. On the other hand, it is the service demands that define the requirements for future 5G technologies. Alignment of both streams will offer fantastic opportunities for vehicular applications in a full broadband wireless environment.

16.8 Conclusion

In this chapter the utilization of LTE as wireless transmission technology for vehicular applications has been analyzed. There is a wide consensus on leveraging the strengths of LTE (high capacity, wide coverage, high penetration) to mitigate the well-known drawbacks of IEEE 802.11p (poor scalability, low capacity, intermittent connectivity).

Future applications have been grouped into four service categories, *Infotainment, Comfort*, *Traffic Efficiency*, and *Safety*. Specific QoS settings have been chosen in order to prioritize the different services. The analysis has been carried out by extensive system-level simulations for different load scenarios and network deployments as well as theoretical investigations.

The results indicate that LTE can meet the QoS requirements of *Infotainment* and *Comfort* services in low traffic-load scenarios. However, especially for high-load scenarios and for uplink transmission the QoS settings have to be carefully selected in order to stay within the required delay budgets of the corresponding services. The additionally generated traffic also has impact on network dimensioning. For *Traffic Efficiency* services, LTE can be considered as a potential wireless transmission technology. The LTE network has to be dimensioned such that sufficient capacity is provided and radio channel quality is sufficiently high. LTE is able to support the delivery requirements of *Safety* services in terms of reliability and delay, under low-to-medium traffic conditions. However, performance decreases under heavy load.

In the initial deployment phase of vehicular networks, LTE is expected to play a crucial role in overcoming situations where no IEEE 802.11p-equipped vehicle is within the transmission range. This could be the case in rural areas where the vehicle density is low. In addition, LTE can be particularly helpful at intersections by enabling the reliable exchange of cross-traffic assistance applications, when IEEE 802.11p communications are hindered by non-line-of-sight conditions due to buildings. The wide LTE coverage can be beneficially exploited for the reliable dissemination over large areas of event-triggered safety messages with advantages for system scalability and congestion control.

Nonetheless, several challenges lie ahead before LTE can be massively exploited in vehicular environments, and a broader understanding of the performance of LTE for the wide set of relevant applications is still required. Studies should not only analyze the capacity of LTE in supporting vehicular applications, as they currently do, but also their potential impact on applications mainly conceived to benefit from this promising cellular technology (e.g., VoLTE, file sharing, video streaming). Moreover, the benefits brought by the augmented capacity and device-to-device capabilities of LTE-A should be analyzed.

Additional discussion is needed for architectural design, vehicular device deployment, and resource management. Standardization requires contributions from different stakeholders toward an integrated and synergetic networking solution leveraging the strengths of LTE, IEEE 802.11p, and emerging communication paradigms like machine-to-machine communications to match the peculiar requirements of vehicular use cases.

Furthermore, future 5G networks are expected to introduce novel technical key components that enable delay-critical services which require high reliability and ultra-low latency. Therefore, 5G will unfold a new level of vehicular connectivity and will be an enabler for even more advanced driver assistance services, such as highly automated driving. Meanwhile, effective business models should be specified to support the wide-spread use of LTE for cooperative intelligent transportation system applications. No one would agree to pay unless highly reliable safety services and attractive traffic related convenience applications can be provided.

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