LTE for Vehicular Networking: A Survey

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ABSTRACT

A wide variety of applications for road safety and traffic efficiency are intended to answer the urgent call for smarter, greener, and safer mobility. Although IEEE 802.11p is considered the de facto standard for on-the-road communications, stakeholders have recently started to investigate the usability of LTE to support vehicular applications. In this article, related work and running standardization activities are scanned and critically discussed; strengths and weaknesses of LTE as an enabling technology for vehicular communications are analyzed; and open issues and critical design choices are highlighted to serve as guidelines for future research in this hot topic.

INTRODUCTION

Enabling wireless connectivity *on wheels* is the aim of several players, driven by the social and economic benefits expected from intelligent transportation systems (ITS) applications, supporting road safety and traffic efficiency through vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications. Safety applications rely on short-message broadcasting in a vehicle's neighborhood to reduce fatalities on the road; traffic efficiency applications need the support of roadside units (RSUs) with communication capabilities to send periodic updates to remote traffic control centers. These applications exhibit some unique features, in terms of generation patterns, delivery requirements, communication primitives, and spatial and temporal scope, which challenge existing wireless networking solutions.

IEEE 802.11p [1] is the standard that supports ITS applications in vehicular ad hoc networks (VANETs). Easy deployment, low cost, mature technology, and the capability to natively support V2V communications in ad hoc mode are among its advantages. Nonetheless, this technology suffers from scalability issues, unbounded delays, and lack of deterministic quality of service (QoS) guarantees [2]. Furthermore, due to its limited radio range and without a pervasive roadside communication infrastructure, 802.11p can only offer intermittent and short-lived V2I connectivity. The above mentioned concerns motivate the recent increasing interest in Long Term Evolution (LTE) [3] as a potential access technology to support communications in vehicular environments.

LTE is the most promising wireless broadband technology that provides high data rate and low latency to mobile users. Like all cellular systems, it can benefit from a large coverage area, high penetration rate, and high-speed terminal support. Extending its use to also support vehicular applications would open new market opportunities to telco operators and service providers. Vehicles are indeed the third place, after homes and offices, where citizens spend more time daily. According to the U.S. Department of Transportation and Safety Administration, commuters spend 500 million hours per week in the car. Alcatel-Lucent's 2009 study showed that over 50 percent of interviewed consumers found the idea of a *connected car* highly appealing, and 22 percent would be willing to pay $30–65 per month for value-added connectivity services while on the road.

Indeed, LTE particularly fits the high-bandwidth demands and QoS-sensitive requirements of a category of vehicular applications known as *infotainment* (information and entertainment), which includes *traditional and emerging Internet applications* (e.g., content download, media streaming, VoIP, web browsing, social networking, blog uploading, gaming, cloud access). In any case, its capability to support applications specifically conceived for the vehicular environment to provide *road safety and traffic efficiency* services is still an open issue.

The main concern comes from the centralized LTE architecture: communications always cross infrastructure nodes, even though all that is required is a localized V2V data exchange, as for safety-critical applications, with negative consequences on message latency. In addition, in dense traffic areas, the heavy load generated by periodic message transmissions from several vehicles strongly challenges LTE capacity and potentially penalizes the delivery of traditional applications.

These topics are under investigation by specialized groups of standardization and government bodies. The European Telecommunications Standards Institute (ETSI), the International Standards Organization (ISO), and the U.S. Department of Transportation (DOT) are currently investigating the complementary roles of IEEE 802.11p, LTE, and other cellular technologies in supporting *cooperative ITS* applications [4–6]. Early works evaluating LTE's effectiveness

Cooperative awareness message (CAM)	**Periodic time-triggered position messages** –Frequency: 1–10 Hz –Max latency: 100 ms –Length: up to 800 bytes (security overhead included) depending on the type of application	**Use cases** –Emergency vehicle warning –Slow vehicle indication –Intersection collision warning –Motorcycle approaching indication –Collision risk warning –Speed limits notification –Traffic light optimal speed advisory
Decentralized environmental notification message (DENM)	**Event-driven hazard warnings** –Max latency: 100 ms –Length: typically shorter than CAMs	**Use cases:** –Emergency electronic brake light –Wrong way driving warning –Stationary vehicle accident –Stationary vehicle-vehicle problem –Traffic condition warning –Signal violation warning –Road-work warning –Collision risk warning –Hazardous location –Precipitation, wind –Road adhesion –Visibility

Table 1. *Safety message requirements and use cases.*

Active road safety applications 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, the transmissions of which can be periodic or event-triggered.

for communications involving vehicles can also be found in the scientific literature [7–15].

The objective of this article is to provide a critical assessment of the LTE capabilities to support the unique set of vehicular applications. First, the state of the art in LTE use for vehicular environments is inferred from the scientific literature and standard documents. Then open challenges are discussed, and predictions about the possible role of LTE in providing services on the road are formulated. To the best of the authors' knowledge, this is the first work that analyzes the cited topic in a systematic way.

Vehicular Applications and Enabling Technologies

Besides infotainment, a set of unique applications have been conceived for users on wheels and classified based on their targets as *active road safety* and *traffic efficiency*.

Active road safety applications 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, the transmissions of which can be periodic or event-triggered. In ETSI documents [16] they are respectively referred to as cooperative awareness messages (CAMs) and decentralized environmental notification messages (DENMs); basic safety messages (BSMs) are the terminology used in [6] for both periodic and event-triggered messages.

CAMs (a.k.a. *beacons* or *heartbeat messages*) are *short* messages periodically *broadcast* from each vehicle to its neighbors to provide information of presence, position, kinematics, and basic status. DENMs are *event*-triggered short messages broadcast to alert road users of a hazardous event. The main requirements of CAMs and DENMs are reported in Table 1, together with the relevant use cases identified by ETSI.

Both CAM and DENM messages are delivered to vehicles in a particular geographic region: the immediate neighborhood (*awareness range*) for CAMs, and the area (*relevance area*) potentially affected by the notified event (congestion, hazard warning, etc.), even spanning several hundred meters, for DENMs. 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.

Traffic efficiency applications aim to optimize flows of vehicles by reducing travel time and traffic congestion. These applications have no strict delay and reliability requirements, but their quality gracefully degrades with increases in packet loss and delay. In this class, the decentralized floating car data (FCD) [17] service requires periodic transmissions of information collected by vehicles, from internal and external sensors (e.g., CAN bus, in-vehicle camera, environmental monitoring sensors), to remote management servers. They process collected data, monitor and predict traffic congestion, and send up-to-date traffic information back to the vehicle's navigation system by also suggesting alternative routes.

Several wireless technologies have been analyzed as candidates to support the mentioned applications through V2V and V2I communications. In agreement with the Communications Access for Land Mobiles (CALM) guidelines, the ITS station reference architecture proposed in ETSI specifications [16] 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 is the most promising one. Early signs of this trend toward heterogeneous networking in the complex vehicular environment can be found in the United States as well [6].

The main candidate access technologies have different characteristics and can match the vehicular applications' requirements, more or less effectively, as summarized in Table 2 and discussed in the next sections.

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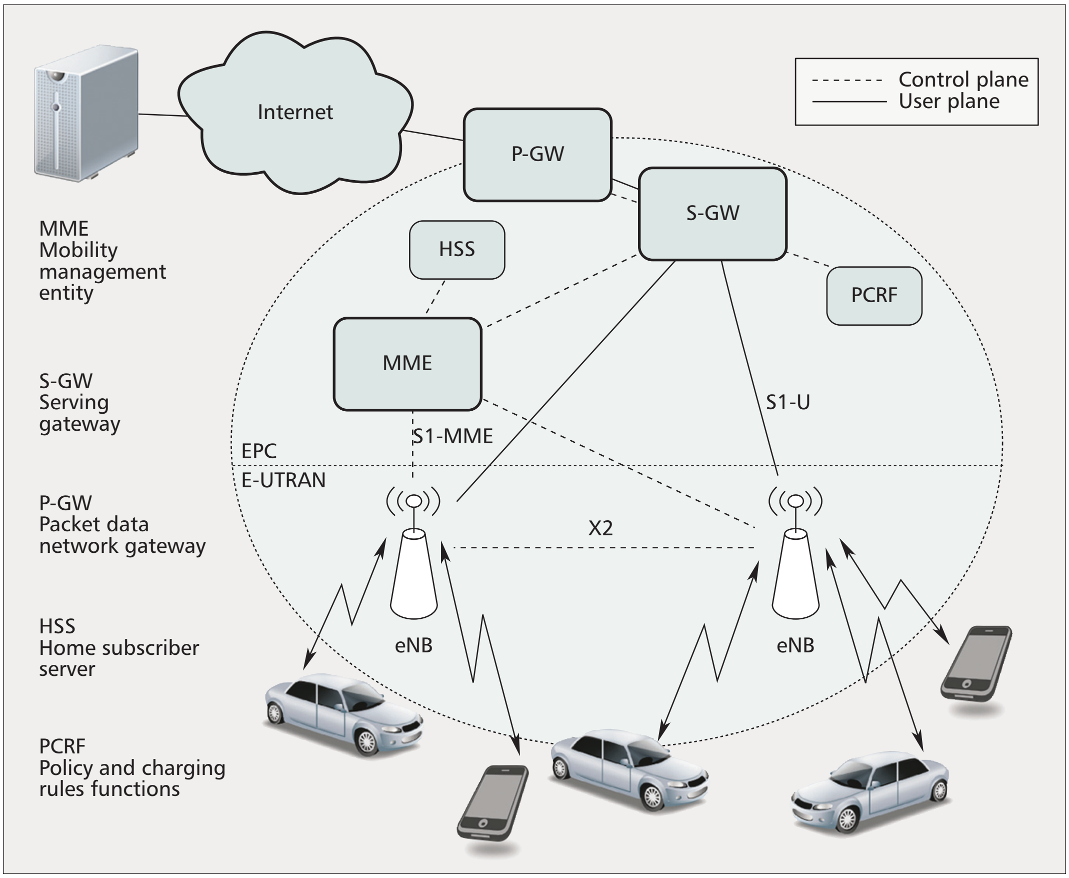

Figure 1. *LTE architecture: access network (eUTRAN) and core network (EPC) entities.*

LTE IN A NUTSHELL

LTE represents the new generation of mobile radio networks defined by the Third Generation Partnership Project (3GPP) [3].

The LTE system is characterized by a *flat all-IP* architecture (Fig. 1) with a reduced number of network devices. IP-based data, voice, and signaling transmissions allow for greater deployment feasibility and extendibility with respect to previous cellular networks. Thanks to its simplified architecture, LTE can provide a round-trip time theoretically lower than 10 ms, and transfer latency in the radio access up to 100 ms. This is especially beneficial for delay-sensitive vehicular applications. The access network is composed of eNodeBs, which manage radio resources and handover events, whereas the core network is composed of three main units: the mobility management entity (MME), responsible for control procedures, such as authentication and security, and storing of users' position information; the S-GW, responsible for routing, data forwarding, and charging by coupling with the policy and charging rules function (PCRF); and the P-GW, the outgoing entity that allows communication with IP and circuit-switched networks.

The LTE air interface has the flexibility to support time-division duplexing (TDD), frequency-division duplexing (FDD), and half-duplex FDD schemes; it also provides scalable channel width (1.4–20 MHz). Concerning the access technology, orthogonal frequency-division multiple access (OFDMA) is used in the downlink and single-carrier frequency-division multiple access (SC-FDMA) in the uplink, both providing high flexibility in the frequency-domain scheduling. Multiple-input multiple-output (MIMO) techniques improve the spectral efficiency by a factor of 3 to 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 (1 ms duration), with the aim of satisfying QoS constraints while increasing channel utilization. A key role is played by the packet scheduler at the eNodeB. It selects the traffic flow to serve, based on the related QoS requirements (as specified by the QoS class identifier, QCI), and decides the appropriate modulation and coding scheme based on feedback from the mobile terminals on the channel quality. QCI refers to a set of packet forwarding treatments, for example, resource type (guaranteed or not guaranteed bit rate), priority, packet loss rate, and delay budget.

LTE also supports high-quality multicast and broadcast transmissions through the evolved multimedia broadcast multicast service (eMBMS) [18, 19] 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 to the offered service, instead of sending it to *every node separately*.

The standardization of LTE-Advanced (LTE-A) is ongoing in 3GPP (Rel. 11) as a major enhancement of LTE in terms of bit rate, capacity, and spectral efficiency, mainly through the

Feature	Wi-Fi	802.11p	UMTS	LTE	LTE-A
Channel width	20 MHz	10 MHz	5 MHz	1.4, 3, 5, 10, 15, 20 MHz	Up to 100 MHz
Frequency band(s)	2.4 GHz, 5.2 GHz	5.86–5.92 GHz	700–2600 MHz	700–2690 MHz	450 MHz–4.99 GHz
Bit rate	6-54 Mb/s	3–27 Mb/s	2 Mb/s	Up to 300 Mb/s	Up to 1 Gb/s
Range	Up to 100 m	Up to 1 km	Up to 10 km	Up to 30 km	Up to 30 km
Capacity	Medium	Medium	Low	High	Very High
Coverage	Intermittent	Intermittent	Ubiquitous	Ubiquitous	Ubiquitous
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)	Enhanced Distributed Channel Access (EDCA)	QoS classes and bearer selection	QCI and bearer selection	QCI and bearer selection
Broadcast/multicast support	Native broadcast	Native broadcast	Through MBMS	Through eMBMS	Through eMBMS
V2I support	Yes	Yes	Yes	Yes	Yes
V2V support	Native (ad hoc)	Native (ad hoc)	No	No	Potentially, through D2D
Market penetration	High	Low	High	Potentially high	Potentially high

Table 2. *Main candidate wireless technologies for on-the-road communications.*

support of advanced MIMO techniques, carrier aggregation, and relay nodes. With LTE-A still in an early stage, the focus of the related work reported in this article is on LTE, but LTE-A potentialities are discussed.

LTE as a Solution to Support Vehicular Applications: Motivations and Concerns

There are several reasons for LTE applicability in vehicular environments; the major issues are discussed in the following.

Coverage and mobility: LTE will rely on a capillary deployment of eNodeBs organized in a cellular network infrastructure offering wide area coverage. This would solve the 802.11p issue of poor, intermittent, and short-lived connectivity, and would particularly indicate LTE for V2I communications even at high node speeds. The LTE infrastructure exploitation would also represent 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 (off-peak hours, rural scenarios, etc.) or to challenging propagation conditions (e.g., corner effect due to building obstructions at road intersections).

Market penetration: A higher penetration rate is expected to be achieved by LTE compared to 802.11p. The LTE network interface will be integrated in common user devices like smart phones, so passengers would be accustomed to being connected to the Internet through these devices while on the road as well.

Capacity: LTE offers high downlink and uplink capacity (up to 300 and 75 Mb/s, respectively, in Rel. 8, and up to 1 Gb/s for LTE-A in Rel. 11), which can potentially support several vehicles per cell. Such values are higher than 802.11p, which offers a data rate up to 27 Mb/s.

On the other hand, some critical issues also raise concerns about the applicability of LTE for supporting the reference vehicular application scenarios.

Centralized architecture: The main concern comes from LTE's centralized architecture, which would not natively support V2V communications, but would instead require passing through infrastructure nodes in the core network that should intercept uplink traffic before redistributing it to the *concerned vehicles*. A myopic message broadcasting over the *entire cell* may reach vehicles that are not interested (e.g., cars moving in the opposite direction to the road hazard advertised by a DENM, or vehicles outside the awareness range of a CAM). Therefore, specialized network entities (e.g., back-end servers) and other core network elements should be involved and wise policies designed for cooperative ITS messages dissemination.

Channels and transport modes: The downlink transport mode (unicast or broadcast) and the selected uplink/downlink transport channels

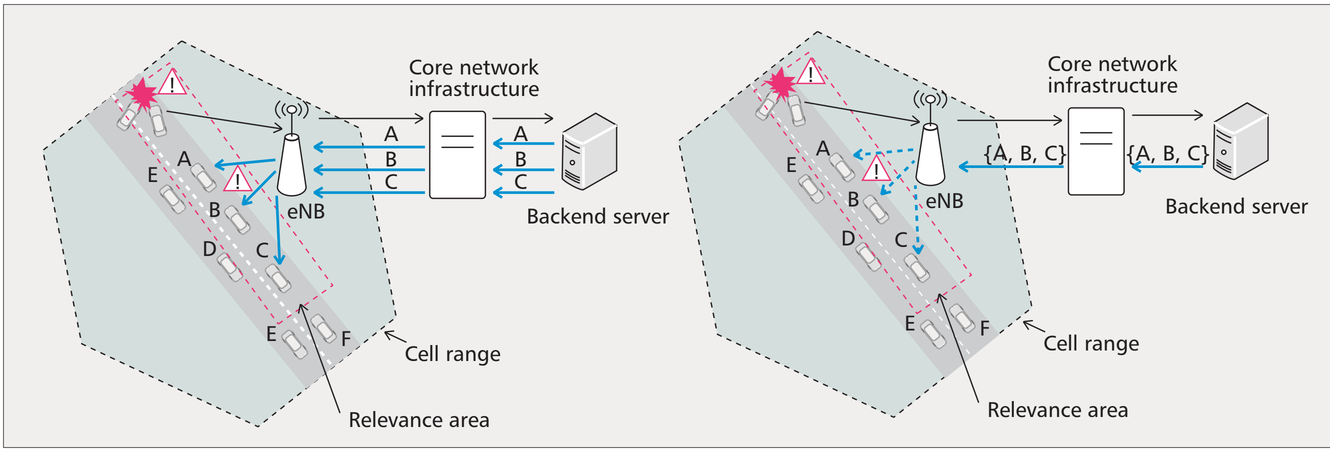

Figure 2. *Unicast (left) and multicast (right) DENM delivery in LTE. Only vehicles within the relevance area (rectangular red area) are addressed.*

(e.g., dedicated or common channel) have an effect on the delay and capacity in terms of the maximum number of vehicles per cell.

Status mode of the device: Latency is also influenced by the *status mode* of the mobile terminal. In order to save resources, cellular networks are configured to keep non-active terminals in *idle* mode, but the connection setup necessary to switch to *connected* mode before sending data may take a longer time than the simple transmission delay.[1] Vehicles should be in connected mode to send periodic CAMs, whereas the transmission of an event-triggered DENM could require a vehicle to switch from idle to connected mode.

LTE Applicability to Vehicular Scenarios: Preliminary Studies

The above mentioned critical issues motivated the recent investigation in the scientific literature and standardization groups in order to assess the applicability of LTE to support vehicular applications. The related work surveyed in this section focuses on safety and traffic efficiency applications that have mainly attracted the interest of the researchers in the field.

Safety Traffic: The CAM and DENM Cases

Safety applications require periodic V2V data exchanges in a vehicle's neighborhood (this is the case of CAMs) or event-triggered V2V and V2I communications (this is the case of DENMs). ETSI and ISO are currently investigating LTE's ability to support these cooperative applications; preliminary results are reported in [4].

CAM and DENM exchanges in LTE involve transmissions from vehicles to infrastructure nodes, and successive traffic distribution to the concerned vehicles.

Regarding the transportation modes, *unicast* is always used for uplink transmission, while unicast and broadcast modes can be used on the downlink by leveraging MBMS capabilities. 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 CAMs and DENMs. In the downlink case, broadcast mode is more resource-efficient than unicast mode, although it could imply longer delays due to the MBMS session setup.

In both cases, ETSI specifications foresee the presence of a special-purpose *back-end server* that supports *geocasting*, by intercepting traffic from vehicles and processing it before redistributing it *only to the concerned vehicle(s)* in a given geographical area [4].

In order to identify the concerned vehicles in a given area and act as a *reflector* [7], the back-end server has to know the list of geographical areas, their coordinates, the cars in any area at all times, and their IP addresses and positions. According to the ETSI specifications [4], each time vehicles cross over to a new area, the server informs them about the coordinates of their current geographical area. The area size can vary from application to application, thus affecting the signaling overhead. Then, whatever the server location, data is distributed to concerned vehicles through MBMS or via multiple unicast connections.

Different approaches to server deployment have dissimilar impacts on the signaling procedures, as discussed in [7]. If the server is installed in the mobile operator's core network, then it may exchange location information with the MME module in the LTE architecture in Fig. 1, which regularly receives location updates from the connected vehicles. If the server is located in the Internet and, thus, decoupled from the mobile operator network, each vehicle maintains a direct connection to the server and regularly sends position updates to it.

Figure 2 reports the example of DENM distribution procedures augmented with the back-end server. In the case of unicast distribution (left), vehicles are addressed *individually*, so that the same message is separately transmitted to all concerned vehicles. In the broadcast/multicast case (right), *all vehicles in the relevance area are collectively addressed*, through *geo-addressing* capabilities leveraging the geographical position of nodes, and a message transmission is performed *once* by relying on MBMS features (dashed lines in Fig. 2). In both cases, latency

[1] *Tests performed on 3.5G networks have demonstrated that idle-to-connected mode switching requires 2 to 2.5 s, which is intolerable for vehicular applications. Lower delay values are expected for LTE, although still not investigated in comprehensive testbeds [3].*

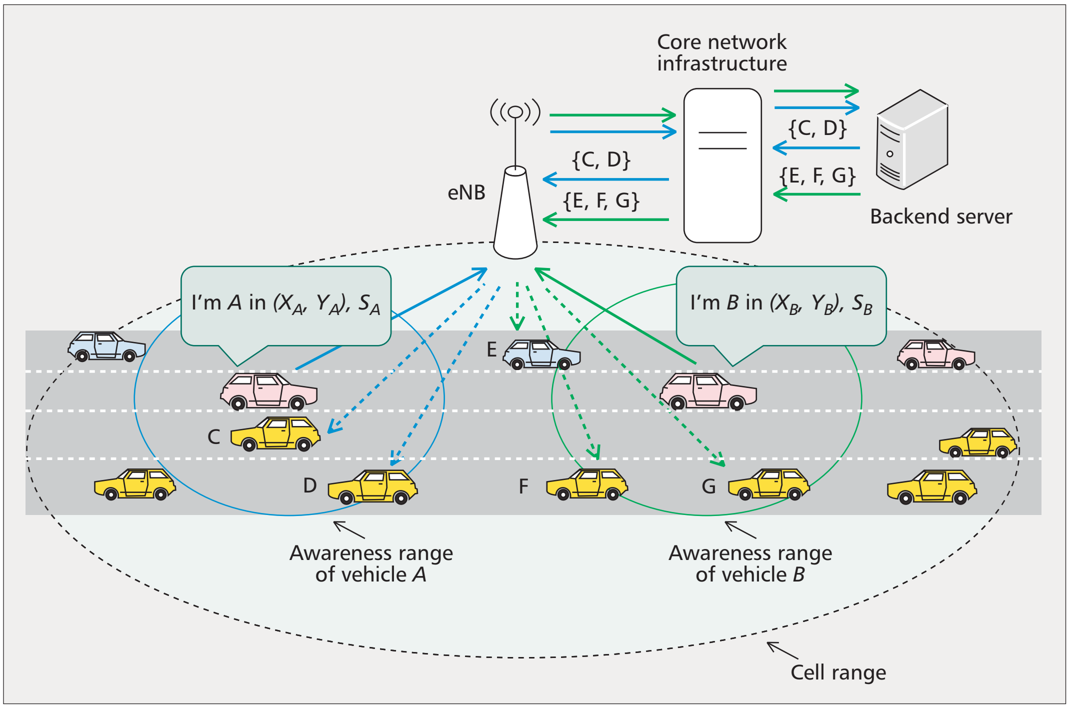

Figure 3. *Multicast CAM delivery in LTE. The awareness range of the vehicles does not coincide with the cell range.*

The main challenge in supporting CAMs is to avoid system overload due to the heavy traffic broadcasted by a high number of vehicles frequently (typically every 100 ms). This is especially critical in dense areas, like city centers, or during peak hours.

could become an issue, especially for localized safety-critical V2V communications.

Even in the case of CAMs, messages have to cross the infrastructure for multicast distribution. In Fig. 3 the back-end server *collectively addresses all vehicles in the awareness range of the sending vehicles* (A and B). On the contrary, in Fig. 4, 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).

CAMs

The main challenge in supporting CAMs is to avoid system overload due to the heavy traffic broadcasted by a *high number* of vehicles *frequently* (typically every 100 ms). This is especially critical in dense areas, like city centers, or during peak hours.

Analytical results in [9] show that LTE is unable to satisfy the CAM delivery requirements when the eNodeB retransmits *all* received CAMs to *every* vehicle in the cell in unicast mode. Similar results are achieved when the eNodeB unicasts CAMs to every vehicle in the one-hop neighborhood. Improvements can be obtained through CAM *broadcasting* in the cell.

In [10] the authors enhance the *unicast* CAM downlink transport with a *filtering* scheme in order to reduce the load and 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 vehicles' location information, the back-end 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 may also easily overload LTE, and a higher number of vehicles per cell can be supported when decreasing the CAM rate down to 2 packets/s. The conducted study contributed to the architecture and the results reported in [4].

The authors finally suggest the use of MBMS as a means to increase the downlink capacity, as also claimed in [11], where the authors advocate the complementary use of cellular systems and 802.11p to successively *broadcast* the received CAMs on the downlink at road intersections, where 802.11p may suffer from non-line-of-sight conditions due to buildings.

The main assumption in the above mentioned studies is that the LTE capacity is *exclusively used* for CAMs, without accounting for other background traffic with different QoS requirements, such as voice or video, traditionally transmitted over LTE. Further investigation is required to analyze:

- The reciprocal interference between CAMs and other traffic types
- The effect of the LTE QoS class selected to carry CAMs
- The effectiveness of *scheduling* techniques deployed at eNodeBs

DENMs

DENMs generate a lower traffic load compared to CAMs; thus, the cell capacity is only temporarily and partially used. In fact, DENMs, generated as a reaction to a hazard, have a limited lifetime, and the number of senders is typically significantly lower compared to CAMs.

The main challenge is related to simultaneous warning transmission attempts by *all* vehicles detecting a specific hazard (e.g., slippery roads; vehicle collision events may be detected and notified by every vehicle passing the area). In this case, again, the back-end server plays the

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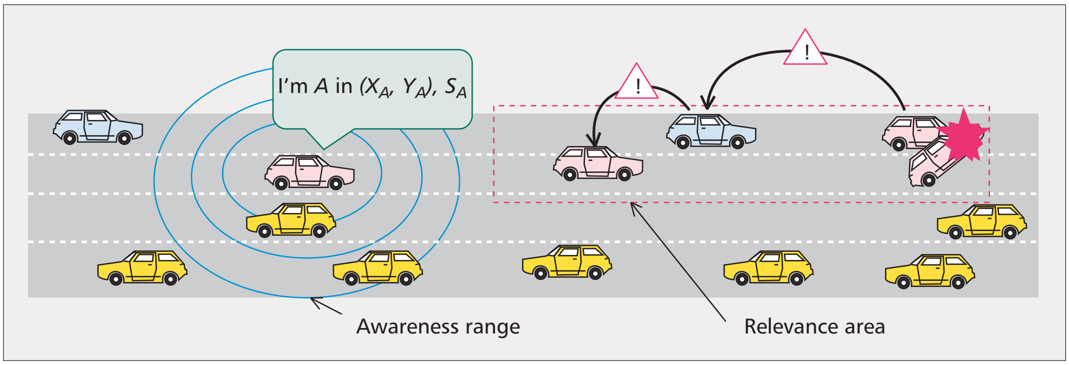

Figure 4. *CAMs and DENMs delivery in IEEE 802.11p. Messages are locally broadcast through V2V communications.*

crucial roles of 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, and send out *only one* consolidated message [4]. This latter feature allows the server to infer a better global view of the road conditions [8]. Such added remote intelligence, which tracks events, can only be offered in a centralized architecture.

In addition, the detecting vehicle receives an implicit acknowledged notification of the same event on the downlink, so it has no need to repeat the same DENM transmission several times. System scalability is thus improved, channel resources saved, and uplink congestion avoided. As an additional benefit, the wide cellular coverage guarantees the event dissemination also when there is no nearby vehicle to relay the message. Therefore, DENM over LTE results in a much more reliable solution as demonstrated in [4, 10] in an empty system, where only DENMs are generated. In [12] 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.

Traffic Efficiency: The Floating Car Data Case

The high deployment costs of a ubiquitous 802.11p roadside infrastructure implies that only a few RSUs will be installed to offer wireless connectivity to vehicles in the near future. Sparse RSU settling and vehicle mobility would cause intermittent and short-lived Internet connectivity with adverse effects on the performance of V2I applications. On the other hand, applications like FCD relying on V2I communications can benefit from the LTE capillary network infrastructure.

Although the latency and reliability requirements are not as strict as for cooperative safety messages, FCD generated by several vehicles can heavily load the uplink channel, thereby threatening the delivery of traditional human-to-human (H2H) traffic. In [13] a channel-aware transmission scheme is proposed according to which vehicles probabilistically transmit FCD based on the measured signal-to-noise ratio (SNR): the higher the SNR, the higher the FCD transmission probability. In doing so, the channel load is reduced, but the distribution of active FCD devices is inhomogeneous, opposite to what is required for reliable and accurate traffic forecasts.

To reduce the traffic load generated by FCD traffic, a hybrid *clustering* framework is proposed in [14] that relies on LTE and 802.11p. The eNodeB is responsible for forming clusters among nodes and selecting one vehicle in each cluster as the cluster head (CH). The CH transmits the FCD from its cluster's members to the eNodeB. The proposed technique achieves significant advantages in terms of bandwidth usage and packet delivery, compared to the case of direct vehicle-to-eNodeB FCD transmission, thanks to the aggregation performed by the CH. Intra-cluster communications leverage time-slotted access on top of 802.11p that shows low overhead and reliability but requires strict synchronization. No details about the LTE scheduling policy and the FCD impact on other traffic types are reported.

LTE in Vehicular Scenarios: Lessons Learned and Open Challenges

The surveyed literature provides some preliminary results, limited to the illustrated cases of CAMs, DENMs, and FCD support, and mostly under the simplistic assumptions of no other traffic types in the system and no specific scheduling policy at eNodeB. In summary, we have learned that:

- Regarding DENMs, LTE can augment 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 in terms of message latency and potential congestion; however, LTE provides advantages in terms of coverage in specific *hostile* areas such as road intersections, where obstacles like buildings can obstruct the line of sight among all vehicles. In summary, LTE offers limited support to CAMs, provided that it can control the CAM generation rule to avoid congestion.
- Considerations on the CAM transmissions

Enabling features	Key issues	Expected benefits
MBMS	• Design of lightweight joining/leaving procedures for dynamic groups of vehicles • Backend server role, task and deployment mode definition to support geo-addressing	Efficient CAMs/DENMs dissemination
Scheduling	• Proper mapping of vehicular traffic patterns to existing QCI and/or new QCI definition • Cross-layer scheduling algorithms accounting for mobility and vehicular communication patterns	QoS support and differentiation No penalization for non-vehicular applications
D2D	• Radio resource management policies to minimize interference in mobility conditions • Mode selection for D2D communication	Localized V2V communications (e.g., CAMs) support eNodeB offloading
MTC	• Efficient transmission of small amounts of data with minimal network impact	Easier management of some ITS applications (like FCD)
Enhanced device	• Powered with the vehicle's battery • Multi-interface platforms	Battery saving Flexibility offered by multi-technology communications
Business models	• Incentive-based approaches • Value-added services provisioning	Larger subscribers basin Higher return-on-investments
Standardization	• Harmonized MTC and ITS standardization activities • LTE role in ITS reference architecture	Enhanced functionalities/architectures New use cases and synergic solutions

Table 3. *A summary of the main deployment issues to support vehicular applications delivery over LTE.*

also hold for FCD on the LTE uplink; they could easily overload the network due to periodic transmissions. However, unlike CAMs, FCD must not be transmitted by all vehicles: studies have demonstrated that the collected traffic information is reliable even if only a small percentage of the vehicles periodically transmit FCD.

•Unicast CAM delivery is less resource efficient than MBMS delivery but it shows advantages in terms of delays, since multicast setup procedures can be avoided that are especially cumbersome under heavy traffic load.

•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 arrived vehicles [8] in the relevant area.

Many other challenges relevant to the LTE capability to support the described vehicular application scenarios definitely require deeper analysis. Some of them uniquely arise for vehicular networking, whereas others are exacerbated in the vehicular environment. The most relevant issues are addressed below and summarized in Table 3.

Multicast/Broadcast Support

MBMS is a promising solution to the localized distribution of cooperative safety applications. However, for MBMS to support geocasting, a back-end server with *geomessaging* capabilities is required, whose role, tasks, and deployment issues should be specified in the LTE architecture. When MBMS operates in synergy with such a back-end server, only the intended receivers are addressed without unnecessarily loading the network and burdening uninterested vehicles with processing load. The drawback could be the signaling overhead due to *subscribe and join* procedures to the multicast service that are performed on a per-user basis. Henceforth, lightweight procedures should be designed to better fit the delay requirements of vehicular applications, especially when *several*, *dynamic*, and *large multicast groups* are to be served. A dedicated MBMS carrier for downlink-only transmissions is advocated in [4], which would eliminate the control overhead for unicast.

Native V2V Support

V2V communications are not natively supported in LTE; therefore, infrastructure nodes must be involved to distribute messages among vehicles. However, research is ongoing to enable direct device-to-device (D2D) communications in LTE-A. In D2D mode, terminals in close proximity *may communicate directly* and offload eNodeB resources. D2D would be an appealing solution for local data exchange among vehicles, but several issues should be addressed for D2D to be really effective [20] in vehicular environments. Radio resource management policies should control the interference between cellular and D2D communications by considering the high

LTE connectivity can easily be provided through common user devices like smart phones. Although early tests demonstrated the leading role of smart phones and mobile apps in the support of vehicular applications, their pervasive use for this purpose is questionable.

mobility of devices. Moreover, the decision about the vehicles' communication mode (cellular or D2D) should account for the feasible D2D range under different vehicle-eNodeB distances:

- To not cause harmful interference to nearby nodes
- To guarantee cooperative road messages dissemination over an area even ranging several hundred meters

Packet Scheduling and QoS Support

Research has focused on the design of LTE packet schedulers that satisfy the often conflicting objectives of high spectrum efficiency, throughput, and fairness. However, the scheduling techniques designed for H2H communications cannot be straightforwardly applied to vehicular applications. In this case, the design of efficient schedulers is especially crucial for the uplink channel, which could be a bottleneck in densely populated networks. On the downlink, instead, the effort is to provide efficient and reliable broadcasting that coexists with the conventional unicast mode. Closely linked to scheduling issues is the mapping of vehicular applications onto LTE QoS classes. There is a wide consensus on the assumption that DENMs should be handled at the highest priority, but no QCI mapping is suggested. This is mainly because, in the surveyed studies, vehicular applications are assumed to be deployed in an "empty" LTE system to assess the best case system capacity. All in all, cross-layer scheduling techniques that account for node mobility and traffic generation patterns, and new QoS classes could be considered to match the vehicular application requirements without penalizing H2H communications.

Amendments to the Standard Documents and Architectures

In order to enable LTE to support *road safety* and *traffic efficiency* applications, some amendments are necessary to the current standard documents and architectures. For example, in the ITS ETSI station reference model, details should be added on the manner of interfacing the LTE access technology. The introduction of LTE as an additional candidate access technology would require some changes in the specification of *use cases* in Table 1. For example, the *emergency vehicle warning service*, currently based on CAMs, can be enhanced by using DENMs in cellular networks. In this case, the position of the emergency vehicle could be used by the back-end server to send DENMs to cars close to the emergency vehicle, but beyond the CAM awareness range, hence allowing the emergency vehicle faster movement.

Machine-Type Communication for Support of ITS Applications

3GPP is working on evolving LTE-A to accommodate the requirements of machine-type communications (MTC), potentially involving a *very large number* of communication devices autonomously (i.e., without human intervention) exchanging *small amounts* of data traffic. It is worth analyzing their relationship with ITS standardization activities. As a matter of fact, 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 as MTC in [21]. Solutions under study in 3GPP for efficient transmission of small amounts of data with minimal network impact (e.g., signaling overhead, network resources, delay for real location) also show promising benefits for supporting the mentioned ITS applications over LTE-A.

Device Deployment

LTE connectivity can easily be provided through common user devices like smart phones. Although early tests demonstrated the leading role of smart phones and mobile apps in the support of vehicular applications [17], their pervasive use for this purpose is questionable. The major concerns are raised by a possible cause of distraction for the driver, the battery-powered nature of these devices that would require specific care in designing energy-saving protocols and circuits, and the non-permanent availability of these devices (e.g., if they are switched off or out of battery, or if they are busy in a traditional voice communication). As an alternative solution, dedicated hardware could be deployed, that is, an onboard unit powered by the vehicle's battery system, and endowed with one or multiple radio interfaces (e.g., IEEE 802.11p, LTE, positioning systems, in compliance with the ITS ETSI station). Despite preliminary attempts, the automotive industry does not see the value of adding such an expensive converged networking platform into vehicles unless a stable and convenient business model is conceived.

Connection Costs and Business Models

Besides the discussed technical issues, economic issues should also be handled. Since LTE operates in licensed spectrum, vehicles' owners may be charged communication costs for data exchange. The costs could be not negligible when the data traffic is heavy and frequent, as is case with FCD and CAMs. Despite the diffusion of always-on Internet connectivity encouraged by flat-rate subscriptions, users could be reluctant to bear the communication costs, unless attractive value-added services are provided. The market value associated with on-the-road service provisioning could be huge; thus, new business models should be conceived between the involved parties: telco operators, road transport authorities, service providers, and users.

Conclusions

In this article we provide a survey on the state of the art of LTE in the view of assessing its capability to support cooperative ITS and vehicular applications. There is a wide consensus on leveraging the strengths of LTE (high capacity, wide coverage, high penetration) to face the well-known drawbacks of 802.11p (poor scalability, low capacity, intermittent connectivity). The conducted analysis qualitatively captures the main features, strengths, and weaknesses of the standard guidelines and solutions under development.

In the initial deployment phase of vehicular networks, LTE is expected to play a critical role in overcoming situations where no 802.11p-equipped vehicle is within the transmission range. This could be the case in rural areas where the car density is low. In addition, LTE can be particularly helpful at intersections by enabling the reliable exchange of cross-traffic assistance applications, when 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., VoIP, file sharing, video streaming). Moreover, the benefits brought by the augmented capacity and D2D capabilities of LTE-A should be analyzed from scratch.

Additional discussion is needed for architectural design, vehicular device deployment, and resource management. Standardization requires contributions from different stakeholders toward an integrated and synergic 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.

Meanwhile, effective business models should be specified to support the widespread use of LTE for cooperative ITS applications. No one would agree to pay unless highly reliable safety services and attractive traffic applications can be provided.

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