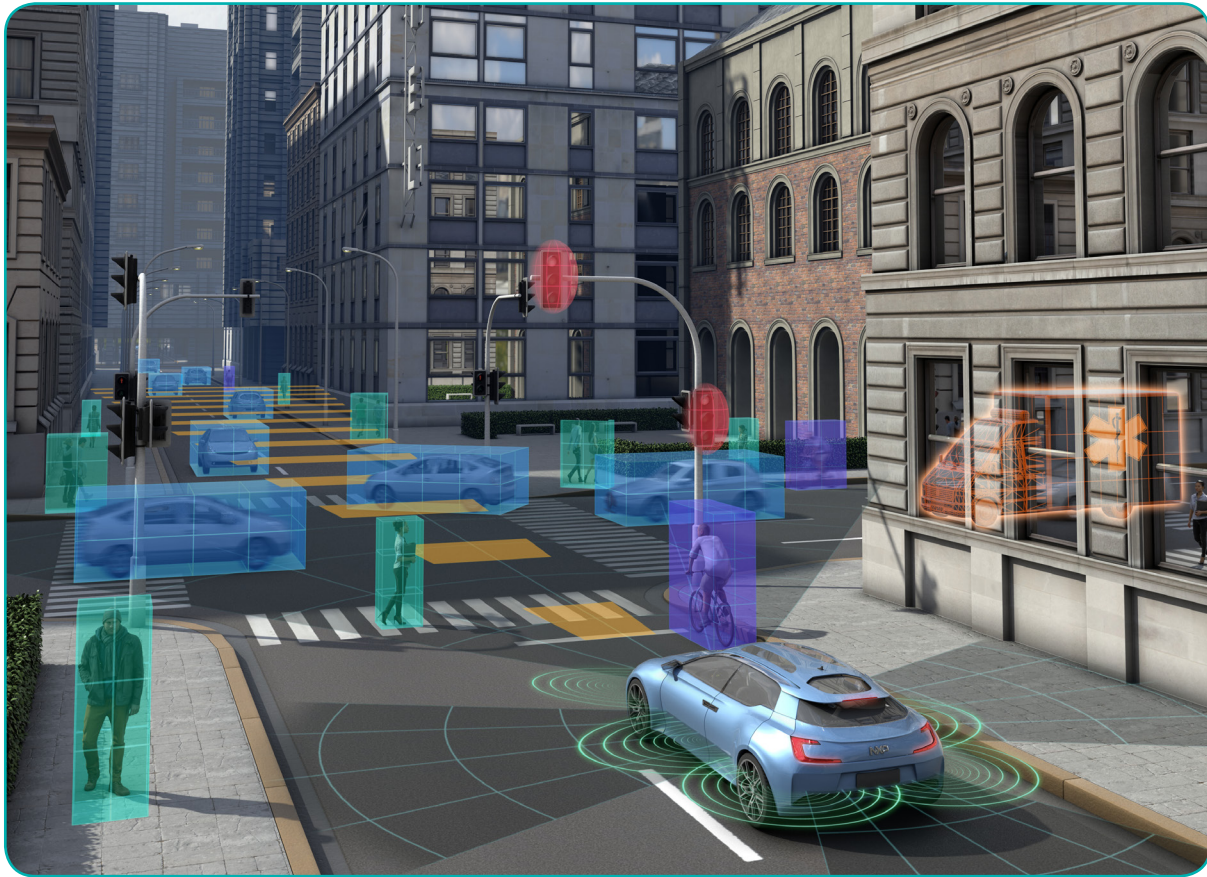


IEEE802.11p ahead of LTE-V2V for safety applications

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Executive Summary

Car-to-car communication is attracting significant attention as it promises to drastically reduce road fatalities, improve mobility and enable a high-level of vehicle automation. Supporting safety critical applications is at the core of car-to-car communication, and for years, the technology of choice for V2X has been IEEE802.11p. Recently, a new standard addressing V2X applications has started evolving under the umbrella of 3GPP, whose focus is mobile broadband standardization. Because the safety of millions of road users will depend on the performance of these technologies, it is important to compare them.

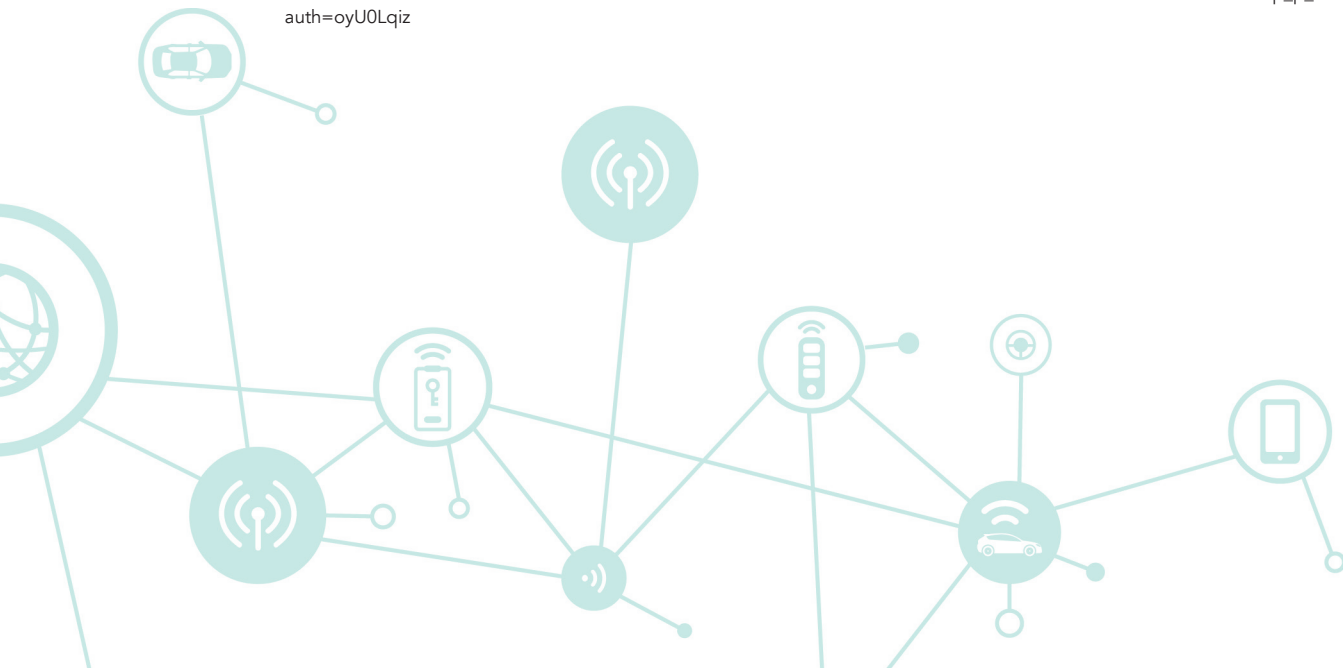
There are several relevant facts important to highlight when comparing IEEE802.11p to LTE-V2X:

- IEEE802.11p is ready now, LTE-V2X is not [4]. Today, IEEE802.11p-based products are available on the market from multiple silicon vendors. Some Tier1s have complete solutions available. In contrast, there is no LTE-V2X product available in the market today, and it will most likely take several years before a complete solution will be ready and tested. The promised 5G version of V2X will have an even longer time horizon;
- IEEE802.11p is already installed in cars on the road. An end-user can buy a vehicle (e.g. GM Cadillac¹) equipped with IEEE802.11p technology today;
- The V2V NPRM has been published [1]. It clearly indicates that the US Government apparently has the intention to deploy IEEE802.11p as a technology thoroughly tested, validated and available for safety critical applications;
- IEEE802.11p mass deployment could begin soon. Volkswagen, one of the largest car manufacturers worldwide, publicly announced that from 2019 onwards, they will equip their first model series with IEEE802.11p technology².

The cellular community is advocating that V2X implementations should wait for cellular technology to be ready and tested, and disregard the investments and field tests done to validate IEEE802.11p for safety critical applications. More concretely, the cellular community claims that LTE-V2X offers:

- a strong cellular eco-system which leverages years of experience in providing paid-services and a mature technology available worldwide. This is a valid argument, but it refers to entertainment services in a cellular-based technology. The communication between a device and a base-station is fundamentally different from the device-to-device communication in a dynamic environment;
- twofold better performance [6]. However, it is IEEE802.11p which outperforms LTE-V2X in important V2V use cases as we show in this article;
- minor added cost. This is questionable as the support of safety critical applications strongly indicates the need to separate those from the entertainment SW and HW. Therefore, LTE-V2X will likely be physically separated from the cellular modem;

1 <http://media.cadillac.com/media/us/en/cadillac/news.detail.html/content/Pages/news/us/en/2017/mar/0309-v2v.html>
2 https://www.volkswagen-media-services.com/en/detailpage/-/detail/With-the-aim-of-increasing-safety-in-road-traffic-Volkswagen-will-enable-vehicles-to-communicate-with-each-other-as-from-2019/view/5234247/6e1e015af7bda8f2a4b42b43d2dcc9b5?p_auth=oyU0Lqiz



- a roadmap of evolution and future proof technology due to the continuous effort in improving the technology via the well-tested mechanism of the 3GPP meetings. While this might be true, introducing an updated standard every 12 to 15 months does not guarantee that older vehicles will be able to communicate with newer ones. This is in contrast with the need of creating a stable and universal international standard to enable the success of V2X technology.

The proposed LTE-V2X technology is a derivative of the cellular uplink technology that maintains similarity with the current LTE systems: frame structure, sub-carrier spacing, clock accuracy requirements and the concept of a resource block, to mention a few. These properties were not made to fit the vehicular use cases, but rather are inherited from existing cellular technology. Consequently, LTE-V2X struggles to meet the specific application requirements of car-to-car communications.

Technically, LTE-V2X suffers when there is no network to support the communications. It has stringent synchronization requirements (section 2.1), it cannot properly receive messages from nearby and closed-by transmitters (section 2.3) and it's limited in its maximum range (section 2.4). Furthermore, it proposes a resource allocation scheme that does not properly handle messages with variable size (section 2.5) and a multiple user access mechanism that is not well suited for broadcasting messages (section 2.6) or for handling collisions of messages (section 2.9). The heavy-weight design of LTE-V2X translates into a higher overhead (sections 2.7 and 2.8).

Commercially, LTE-V2X cannot leverage the presence of the standard LTE modem in the car. Different safety requirements (section 2.10) and technology needs (section 4.1) strongly suggest that the safety critical domain of LTE-V2X will be separated from the entertainment domain of the standard LTE modem. The stringent synchronization requirements (section 3.2) could significantly increase the costs in the LTE-V2X hardware.

Strategically, LTE-V2X might not be the best technology for safety critical applications as its fast development cycle does not match the automotive development cycle (section 4.1). The 3GPP community has already started working on a new version of LTE-V2X while the current version has not been tested in the field yet. The next generation of IEEE802.11p is also being considered (section 4.2.1) to capitalize on the experience of multiple large-scale field trials to test safety critical applications.

Our conclusion is that IEEE802.11p technology is ideal for safety critical applications that must be supported in absence of a network. If the cellular infrastructure is available, LTE-V2X is a valid alternative and offers a more mature eco-system for entertainment services. The win-win situation would be to focus on the strongest points of each technology and work together to provide the best car-to-car communication solution, continue deploying IEEE802.11p for safety critical applications and ensure that the upcoming LTE-V2X technology can coexist.

1 Introduction

Since its introduction 10 years ago, the technology of choice for V2X has been IEEE802.11p³, which has been standardized, implemented and thoroughly tested. Recently, a new standard addressing V2X applications has started evolving under the umbrella of 3GPP, whose focus is mobile broadband standardization. The safety of millions of road users will depend on the performance of these technologies; therefore, it is of outmost importance for policy makers, vehicle manufacturers and the wider automotive ecosystem to compare them.

1.1 V2X targeted functionality

Working together and sharing information to make transportation safer, greener, and more enjoyable, is truly compelling. The technologies associated with this concept, collectively known as Cooperative Intelligent Transportation Systems (C-ITS), promise to reduce traffic congestion, lessen the environmental impact of transportation, and significantly reduce the number of lethal traffic accidents.

A key enabling technology of C-ITS is wireless communication, covering vehicle-to-vehicle (V2V) communication, vehicle-to-motorcycle (V2M) communication, vehicle-to-infrastructure (V2I) communication, and infrastructure-to-vehicle (I2V) communication. Collectively, these wireless transactions are referred to as vehicle-to-everything, or V2X, communication.

V2X technology will support many safety-related and possibly the non-safety-related use-cases of C-ITS systems. It needs to operate robustly in a very dynamic environment with high relative speeds between transmitters and receivers, and support the extremely low latency of the safety-related applications in fast highways, crowded urban intersections and tunnels.

1.2 IEEE802.11p

IEEE802.11p was designed to meet every V2X application requirement with the most stringent performance specifications. In 1999, the U.S. Federal Communications Commission (FCC) set aside 75 MHz of spectrum, in the 5.9 GHz region, for V2X. The IEEE802.11p standard operates within this range.

IEEE802.11p is an extension of IEEE802.11a (WiFi), operating in an ad-hoc network mode without the need of a BSS (Basic Service Set, the WiFi 'base station'). It is optimized for mobile conditions in presence of obstructions, handling fast-changing multi-path reflections and Doppler shifts generated by relative speeds as high as 500 km/h. The typical Line-Of-Sight (LOS) range is 1 km, but the main purpose of IEEE802.11p is to 'see around corners' (NLOS, Non Line Of Sight) as no other sensor in the car is able to do. It has been shown that with state-of-the-art technology, currently available as commercial off-the-shelf products, larger ranges of even several km are routinely achievable. IEEE802.11p multiple access mechanism (the Carrier Sense Multiple Access protocol with Collision Avoidance, CSMA-CA protocol) efficiently handles high density use cases when combined with Distributed Congestion Control (DCC) [7].

3

Formally named IEEE802.11 operating outside the context of a BSS, and also known in the USA as DSRC

The standardization work started more than 10 years ago, a final draft was approved in 2009, and has been extensively tested and validated since that approval. The first large-scale field test, the simTD project [8], began in 2009 and included over one hundred vehicles. Dozens of additional field trials with commercial IEEE802.11p products have been completed since then, while many are still on-going. To mention a few, see [8-13]. One of the biggest running pilots for IEEE802.11p is funded by USDOT (in Wyoming, Tampa and New York city) including over ten thousand vehicles implementing diverse applications and an investment of more than \$45 million [13]. Large investments are being made to guarantee the quality and reliability of this technology.

Several semiconductor companies have designed and tested automotive qualified IEEE802.11p-compliant products. A large number of hardware and software products are available from multiple suppliers, comprising a rich ecosystem. There are several car models on the market with IEEE802.11p technology, while others are planned to be launched soon, for example:

- GM's Cadillac CTS is equipped with IEEE802.11p⁴ ;
- Toyota has close to 100,000 cars in Japan equipped with IEEE802.11p;
- Volkswagen selected IEEE802.11p technology to support V2X applications⁵.

The USDOT has declared, based on collected evidence, that IEEE802.11p technology can significantly reduce the number of collisions on the road. Experts expect that the USDOT is in the process of mandating the use of IEEE802.11p in all new light vehicles for safety-related use-cases [14].

1.3 LTE-V2X

LTE-V2X is a relatively new technology (first discussions took place in 2015), and is an extension of 3GPP Rel-12 Device-to-Device (D2D) functionality, which itself is based on using the LTE uplink transmission and uplink spectrum resources for direct communication between devices. Basic safety V2V functionality made its debut in LTE Rel-14 specification.

LTE-V2X was designed with multiple deployment scenarios in mind, leading to the following requirements:

1. Operation with or without eNB ('base station') coverage. LTE-V2X in Rel-14 is based on the PC5 interface that allows users to directly broadcast messages to each other, with or without network coverage. Operation under cell-coverage is leveraging all the benefits of a synchronous network, where central coordination, scheduling and management is realized by a series of base-stations. However, it should be noted that many scenarios exist where this setup cannot be operated, e.g. in rural areas with poor coverage, and highways and fast-speed users with many handovers. Reliable operations without coverage must be addressed by LTE-V2X technology;

4 <http://media.cadillac.com/media/us/en/cadillac/news.detail.html/content/Pages/news/us/en/2017/mar/0309-v2v.html>

5 https://www.volkswagen-media-services.com/en/detailpage/-/detail/With-the-aim-of-increasing-safety-in-road-traffic-Volkswagen-will-enable-vehicles-to-communicate-with-each-other-as-from-2019/view/5234247/6e1e015af7bda8f2a4b42b43d2dcc9b5?p_auth=oyU0Lqiz

2. Standalone operation on a dedicated unlicensed carrier or under licensed spectrum;
3. Enhanced D2D air-interface functionality for supporting low-latency, high-density and high speed.

To address the enhanced requirements, Rel-14 LTE-V2X introduced new Sidelink transmission modes (Transmission Modes 3 & 4), see Table 1. These differ from Rel-12 D2D modes (TM 1 & 2) by introducing low-latency transmissions, improved support for higher speed and new distributed channel access mechanism [15].

	Scheduling method	Channel access	Use case	Release
Mode 1	eNB	eNB-controlled	Public safety VoIP	LTE Rel-12
Mode 2	Distributed	Random, with blind re-transmissions	Public safety VoIP	LTE Rel-12
Mode 3	eNB	eNB-controlled	V2X	LTE Rel-14
Mode 4	Distributed	Sensing, with semi-persistent transmission	V2X	LTE Rel-14

Table 1: available operation modes in LTE-Sidelink Communications

Despite the recent contributions and standardization efforts, the LTE-V2X standard has not reached maturity, and many technical topics are still being discussed, leading to some significant standard changes agreed upon during the last RAN meetings. The number of maintenance Change Requests (CR's) related to V2X is large and makes it challenging for chip makers to settle on a set of functionalities, reach interoperability testing stage, freeze the hardware and software architecture and go to production. Automakers might also question the effective performance and support of the safety-critical use cases. At this point in time, the real-life performance of the LTE Rel-14 standard is practically unknown.

The most relevant and challenging LTE-V2X operation mode for the safety-critical applications is Sidelink Transmission Mode 4, which can be seen as an ad-hoc mode. The comparison with IEEE802.11p technology will focus on this mode.

2 Comparison of LTE-V2V Mode 4 versus IEEE802.11p

Both IEEE802.11p and LTE-V2X use the well-known Orthogonal Frequency Division Multiplexing (OFDM) as a modulation technique, in which a block of data is transmitted on equidistant subcarriers. However,

	IEEE802.11p	LTE-V2X
Multi-user allocation	single user per symbol	multiple users share the same symbol
Synchronization requirements	asynchronous	tight synchronization
OFDM parameters	short symbol duration	very long symbol duration
Channel access mechanism	CSMA-CA	sensing based SPS transmission

Table 2 Difference between IEEE802.11p and LTE-V2x design parameters

as reported in Table 2, they choose very different parameters. LTE-V2X has inherited much of LTE mechanism which is suitable for centralized (i.e. non-ad-hoc) and synchronized network, with power control, synchronization adjustments and which operates with low to moderate speed. As we show in the following sub-sections, it is less suitable for ad-hoc communication mode and fail in several important V2X use-cases.

2.1 Synchronization

LTE-V2X is more sensitive to frequency errors and timing errors than IEEE802.11p. With inaccurate frequency synchronization, the residual frequency errors lead to Inter-Carrier Interference (ICI). In LTE-V2X the OFDM subcarriers are 10 times closer than in IEEE802.11p so the same absolute frequency error has significantly more impact in LTE-V2X than in IEEE802.11p. Consequently, LTE-V2X performance is limited, and the same absolute frequency error generates 100 times larger interference power [10]. This is quantified in the time and frequency accuracy requirements of IEEE802.11p and LTE-V2X summarized in Table 3.

	Timing accuracy		Frequency accuracy	
	allowed error [μsec]	Reference	Allowed error [ppm]	Reference
IEEE802.11p *	± 1000	Absolute (UTC)	± 20	Absolute
LTE-V2X **	±0.39	sync source	±0.1	sync source

Table 3 - transmit accuracy requirements.

* timing accuracy is specified in IEEE 1609.4 for channel switching.

IEEE802.11p operation has no timing dependency; frequency accuracy is specified in IEEE802.11

** timing accuracy is specified in 3GPP TS 36.133; frequency accuracy is specified in 3GPP TS 36.101

Two main differences are apparent:

1. LTE-V2X requirements are much more demanding;
2. LTE-V2X requirements are relative to the user's synchronization source. When users have different synchronization sources, such as locking to different base stations, the requirements can no longer be maintained thus impacting performance when vehicles are communicating with one another.

To address the synchronization requirements, LTE-V2X users rely on the Global Navigation Satellite System (GNSS) signal. However, this brings other challenges. For instance, it is a fact that the GNSS signal is not always available or not reliable enough in locations such as tunnels, underground parking lots and urban canyons. With no GNSS coverage, keeping synchronization within the required accuracy boundaries depends on the drift of the local oscillator of the user. The higher the accuracy, as required by the tight subcarrier spacing, the higher the costs. In the absence of reliable GNSS signal or no GNSS signal at all, a user will have to select an alternative source for synchronization which impacts reliable communications.

IEEE802.11p operation does not depend on GNSS signal. IEEE1609.4 requires the GNSS signal as well, but simply to switch from one channel to another, i.e., with much lower time and frequency accuracy.

2.2 High speed conditions

Transmissions by moving vehicles introduce Doppler frequency shifts, which can be seen as additional frequency errors (in addition to synchronization errors). Under high speed conditions these Doppler frequency shifts can be two times or even four times larger than the synchronization errors (increasing with the vehicle relative velocities) and become dominant.

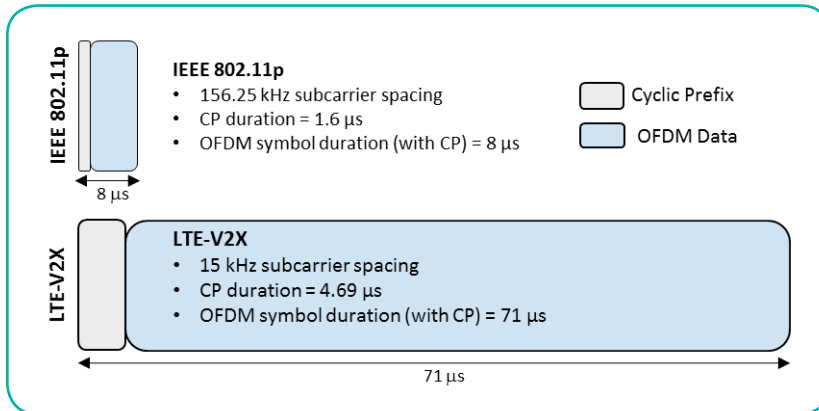


Figure 1 OFDM symbol of IEEE802.11p (top) and of LTE-V2X (bottom), at scale

As shown in Figure 1, in LTE-V2X the symbol duration is ten times longer than that of IEEE802.11p which puts a limit on the maximum detectable Doppler frequency shift, and therefore maximum limit on speed (in addition of tracking the fast-varying channel). In fact, this drawback was already observed internally in 3GPP simulation results where beyond a speed of 140km/h, messages are no longer detected reliably and performance is quite poor [19]. The attempt of 3GPP to overcome the problem was by introducing complex processing methods which were found not to be robust enough [20] or by reducing the modulation and coding scheme (MCS) which did not solve the problem. Proposing to change the pilot symbols pattern or shorten the symbol duration [21] was not accepted and eventually LTE-V2X is strictly limited to speeds below 140km/h.

IEEE802.11p on the other hand, benefits from very short symbol duration and selected a symbol pilot pattern such that does not impose any limit on performance in high-speed. And while LTE-V2X is limited to operate below 140km/h, IEEE802.11p can perform well even at speeds of 250km/h or beyond.

2.3 Near-far problem

LTE-V2X is sensitive to the scenario in which a user receives a signal from two or more transmitters with different power levels, i.e., the near-far problem, as illustrated in Figure 2. The power difference may occur even for two nearby transmitters, when one of those is obstructed. IEEE802.11p allows a single user transmission for each OFDM symbol, and the receiver sets its parameters, like the automatic gain controller (AGC), the time offset estimation and the frequency offset estimation, in the best possible way for each user independently, as symbols are not shared.

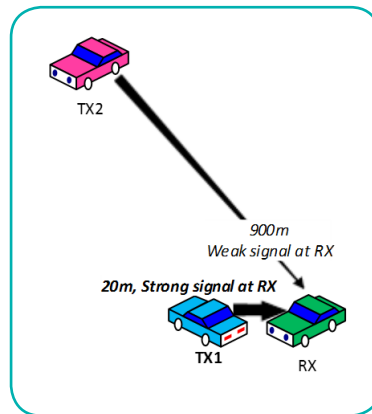


Figure 2 Near-far problem: receiving two simultaneous signals

LTE-V2X allow users to share resources within the same OFDM symbol (Figure 3), but the receiver will only set its AGC gain based on a single combined signal. Therefore, the ability of LTE-V2X receiver of detecting weak messages in the presence of strong messages is limited⁶. The weak message may have higher importance than the strong one. For example, the strong message may be received from a transmitter behind the vehicle having low relevance to safety decisions, while the weak message may arrive from an approaching transmitter that might impose a real risk.

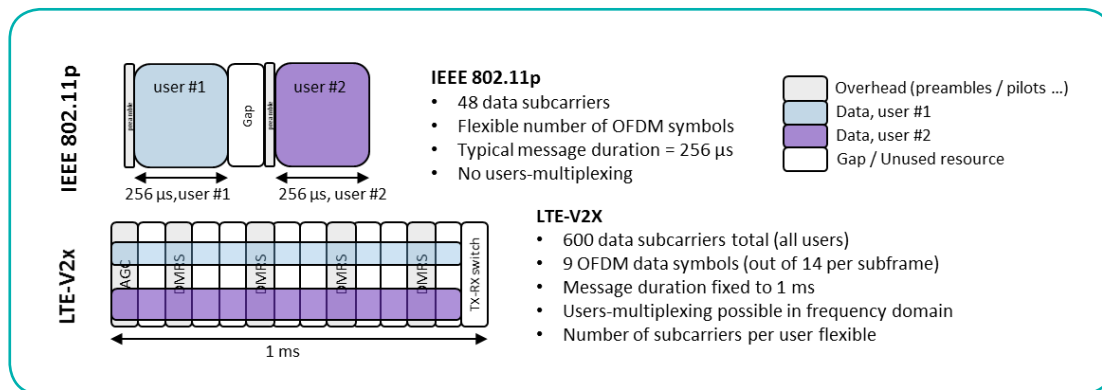


Figure 3 Frame structure of IEEE802.11p and LTE-V2X with an example of resource allocation, with two users transmitting a CAM message of 192 bytes with QPSK and coding rate $\frac{1}{2}$. Note the sharing of the symbol in case of LTE-V2X.

To address the near-far problem, LTE-V2X introduces the concept of geo-zoning. This consists of creating spatial isolation where users in different locations would be limited to select resources for transmissions from a certain time-frequency set, based on their absolute geographical location. This solution is certainly interesting, but needs to be validated in the field to assess the impact of the non-uniform distribution of users and their rapidly changing location.

⁶ Due to the limitation of practical dynamic range

2.4 Maximum range

One way for comparing V2X technologies can be based on real performance tested in outdoor under similar conditions. IEEE802.11p proved to achieve large communication ranges in various field trials, and several kilometres' range has been achieved in highway situations [8]. Unfortunately, LTE-V2X field trials are not yet available to compare with. But the LTE-V2X synchronization concept puts a limitation on the communication range between users, which is reflected in the different role assigned to the cyclic prefix (CP), see Table 4:

	IEEE802.11p	LTE-V2X
CP duration	1.6 μ s	4.69 μ s
CP purpose	Delay spread	Timing errors, propagation delay, and delay spread

Table 4 Size and purpose of the Cyclic Prefix (CP) in IEEE802.11p and LTE-V2X

In synchronous systems like LTE-V2X, the signal of all users must arrive time-aligned to the receiver to prevent inter-symbol interference between consecutive OFDM symbols. In practice, this cannot be achieved as either the signal propagation times from different transmitters are unequal, or because timing reference that each user is using for its own transmission is not equal. One example is when users are in coverage and using eNB as their timing reference (in cases where GNSS is not reliable). In this case, each user transmission timing is based on its own downlink timing reference⁷. Naturally, some users are located near eNB (having short propagation delay) and some located further away. Near users will begin their transmission earlier than far users and RX users located next to near users will also set their receive window in accordance. The transmission of far users will arrive at the RX after the round trip propagation delay. In case the far transmitter is too distant, it will arrive too late beyond the receive window, and RX side will fail to detect the message, see Figure 4.

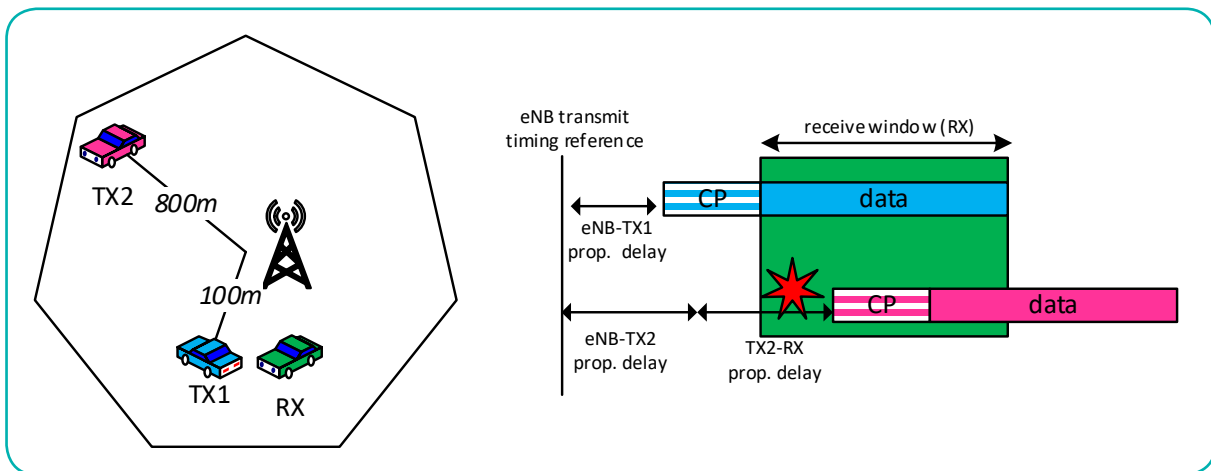


Figure 4 Impact of Cyclic Prefix in distance

⁷ Which is based on downlink transmissions detected from eNB

As can be seen from the figure, there is a limit on the communication range, beyond which a receiver cannot detect messages from far users. Table 5 summarizes the maximum range achievable under LTE-V2X. Some cases cannot meet the NPRM requirements for the Do-No-Pass-Warning message defined in [17].

Conditions	Source for timing reference	
	GNSS	eNB
Ideal (no timing errors and no delay spread)	1407m (1 CP)	703.5m
Realistic (timing errors and 1us delay spread)	873m	436.5m

Table 5 Achievable distance of LTE-V2X based on timing reference source

2.5 Resource allocation

Real-life V2X traffic pattern is characterized by packets with variable size. A set of messages such as CAM (specified by ETSI) and Basic Safety Message (BSM, as specified by SAE) are generated periodically (commonly every 100 ms) including vehicle state information such as geo-location, velocity, heading and other related information. Occasionally a vehicle will attach to these messages also a set of path prediction and/or recent path history points. The number of points depends on the road conditions, but with each point described by ~10 bytes, this added information can easily occupy additional tens of bytes in the payload. Another example of varying message size is related to security: for BSM, the entire security certificate is sent only every 500ms, adding additional 100 bytes to the default message size.

The resource allocation scheme of IEEE802.11p can easily support variable packet size. Once a user occupies the channel, it determines for itself the duration of the transmission with resolution of one OFDM symbols (i.e. 8 ms) so that the payload transmission time is shorter/longer accordingly. In LTE-V2X, users reserve resources in a semi-persistent manner, i.e., before knowing the exact packet size. When reserving resources in advance while the application layer payload size is yet to be determined, reservation will result either in over-allocation (inefficient) or under-allocation of resource size (requiring a more dense coding, reducing detection probability for the message). Either way, the simple resource allocation mechanism for IEEE802.11p is more efficient in handling variable payload size.

2.6 Half Duplex

As is apparent in Figure 3, in LTE two users may transmit in the same OFDM symbol using different frequency resources. At a given moment, a user can either transmit or receive as their radio works in a half-duplex mode. Thus, both users will not receive each other's message even when located closely, and will miss information necessary for safety critical decisions. They will have to wait until one or both of them will select a new resource for transmission.

This problem is tentatively addressed by 3GPP by usage of transmission repetition so that two users which used the same sub-frame for the first transmission would use different sub-frames for the second transmission. From the system perspective, this solution increases latency, halves the network capacity, and causes conflicts in resource allocation thus reducing communication range.

2.7 Physical Layer Efficiency

The heavyweight design of LTE waveform and frame-format translates into higher overhead in case of a single user, as the following table describes.

	LTE-V2X	IEEE802.11p
Data message	20 resource blocks (PRBs)	50 symbols
Overhead data	5 PRBS (2 SA+3 for DTF precoder)	5 symbols (PLCP+SIGNAL)
CP	4.69 μ s	1.6 μ s
Pilots	4 symbols (DMRS)	4 subcarriers
Additional overhead	Guard period (1 symbol)	Service field, tail and padding
Total overhead, physical layer	52.55%	33.97%

Table 6 Overhead comparison between IEEE802.11p and LTE-V2x when sending one CAM message

2.8 Capacity

V2X is intended to work in high traffic densities. Capacity defines the ability of all vehicles in a certain area to communicate without competing for the same resources, eventually leading to degraded communication range and increased latency. IEEE802.11p and LTE-V2X have similar capacity and range under equivalent conditions.

Table 7 shows that capacity in LTE-V2X and IEEE802.11p is similar and a given 10 MHz channel can accommodate about 2 messages during 1 ms.

	LTE-V2X	IEEE802.11p
Transmission duration	Fixed, 1msec	Control (PLCP) = 40 μ sec Data (PSDU) = 50 symbols = 400 μ sec Total = 440 μ sec
Occupied bandwidth	Control (SA) = 2 PRB = 360 kHz Data = 2424 PRBs = 4.32 MHz Total = 4.68 MHz	Fixed, 10 MHz
Capacity	\approx 2 messages / 1ms	\approx 2 messages / 1ms

Table 7 Capacity comparison

2.9 Collisions of messages

There will be multiple users within a given part of a road, each of them transmitting messages at a regular interval. IEEE802.11p addresses the potential collisions by implementing the CSMA-CA protocol which checks if the wireless channel is used before enabling a new transmission. LTE-V2X does not have an equivalent mechanism. If a collision happens, it is not detected. Two users might be transmitting using the same resource block. Resources are kept for several transmissions via a semi-persistent allocation before a re-selection. Therefore, several transmissions of the two users will be lost.

The problem is mitigated in LTE-V2X by adding some level of randomization with respect to the timing of the re-selection events between users, but the risk of collision is not completely solved.

For example, two vehicles may approach an intersection. Once getting into communication range, IEEE802.11p will assure collision free operation and a warning would be issued if necessary. This is not the case in LTE-V2X, where precious time may be lost.

2.10 Cybersecurity protection

Functional safety certification for road vehicles, defined in ISO26262, provides requirements for validation and confirmation measures to ensure a sufficient and acceptable level of safety is achieved. Risk and hazard analysis determines the Automotive Safety Integrity Level (ASIL) grade by weighting the potential to threaten lives. Since V2X may be controlling the vehicle, like in a platooning application, it is assumed that V2X would require ISO26262 with ASIL B grade. Achieving ASIL B grade requires additional costs, strongly suggesting to separate the non-safety critical domain from the safety critical domain, both in terms of HW and SW. If the non-safety part of the system is not isolated, it should also be involved in the ISO26262 certification, which would make it extremely difficult and costly to achieve. Furthermore, the separation of the domain enables a stronger and needed protection from potential cyberattacks, see Figure 5. The hardware and software separation clearly implies that the standard LTE modem cannot be simply re-used to cover the LTE-V2X application space.

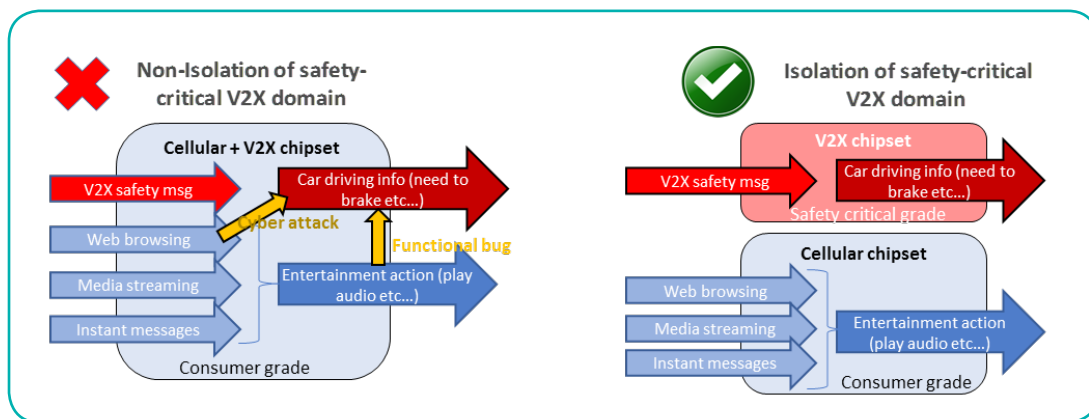


Figure 5: Functional safety & cybersecurity benefits of isolation between safety and non-safety domains

The high complexity of an LTE-V2X solution will imply higher cost than an IEEE802.11p solution. Addressing safety applications with LTE-V2X becomes more expensive.

3 Cost factors

3.1 No re-use of standard LTE modem

A standard LTE modem chipset decodes only a single transmission per-TTI, received from a base station. In LTE-V2X, the chipset is required to decode multiple transmissions (by different users) concurrently per-TTI, in addition to decoding the base station data. Significant amount of hardware should be added. The standard LTE modem cannot be re-used, since the waveform and signal format in LTE-V2X is different than that of standard LTE.

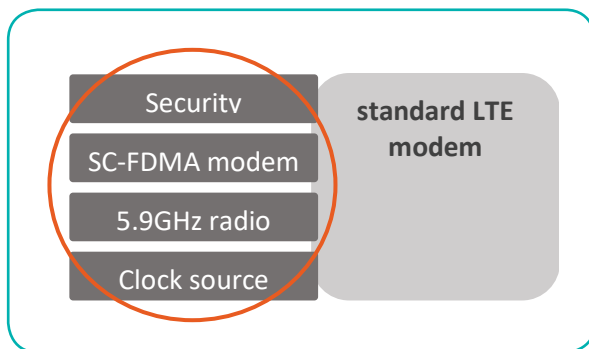


Figure 6 Required additional blocks to a standard LTE modem

Furthermore, a 5.9GHz radio chain should be added, together with the stable GNSS synchronized clock source, see Section 2.1.

Cost-wise, LTE-V2X and IEEE802.11p systems differ only in the modem and clock source, as the higher layers, human-machine interface and safety use cases are the same. It is not far-fetched that an IEEE802.11p modem is less expensive than the extra costs incurred by adding LTE-V2X next to a cellular chipset, due to the LTE-V2X clock source and the impact of certification costs (AEC-Q100 impact on cellular chipset cost). As a result, even without domain separation, LTE-V2X is not less expensive than IEEE802.11p.

3.2 Timing and clock accuracy

The additional sensitivity to accurate synchronization of LTE-V2X implies unrealistic reference clocks, see Table 3, as the accuracy of clock source is related to performance and robustness. High accuracy components, with low drift-rates and stability under high-temperatures and high forces, eventually cost more.

For IEEE802.11p the accuracy requirements are almost no different from that of commodity WLAN devices and therefore synchronization accuracy requirements will not impact the cost of a IEEE802.11p-based system.

LTE-V2X should be able to maintain the same level of accuracy over time even when GNSS coverage is temporarily weak. When LTE-V2X cannot rely on GNSS and cannot find another user which itself is synchronized with GNSS (directly or indirectly), LTE-V2X systems will still have to generate and transmit V2X messages with the stated frequency accuracy of 0.1 ppm. It is an unrealistic requirement for vehicles to meet this accuracy as the required components are very expensive. This level of accuracy is reserved today only to macro base stations (macro eNB), which have integrated high-end oscillators, which are definitely not expected to be used in the consumer terminals, undergoing high temperature variations and susceptible to vehicle vibrations and accelerations.

3.3 Motorcycle / eBikes: No cellular modem barrier for the most vulnerable road users

LTE-V2X without a standard LTE modem is even more cost prohibitive, with significantly higher pricing than IEEE802.11p. Cellular modems are uncommon in motorcycles and eBikes, since eCall regulation does not apply for motorcycles. Therefore, LTE-V2X cost impact on the relative low cost of motorcycle would be a blocker.

Motorcycle positioning is a great challenge due to the high maneuverability of motorcycles. GNSS and V2X antennas should be carefully placed and should not depend on the unknown position, orientation and shielding of a smartphone. Therefore, using smartphones to support V2X applications is not a suitable alternative. IEEE802.11p is the least expensive active safety mechanism for motorcyclists, which have the utmost need for V2X protection.

4 Maturity and Outlook

4.1 Sample Automotive Cycle

The pace of the automotive market is quite different from the pace of the cellular market. Where a mobile phone is typically replaced every 3 years, a car will be on the road for 15-30 years, and be required to operate reliably over this time span. Technology therefore must be mature and well-proven. A recall in the case of failures has significant consequences, as the act of returning a car has a different impact than returning a smart phone.

For this reason, there are extensive quality measures for automotive components with respect to reliability, life span, and operating conditions in order to guarantee a low drop-out rate (typically below 1 part per million). This spans not only the design cycle, but also testing and qualification.

As V2X will be essential in (semi-) autonomous driving, we expect it to be at least qualified for use in systems at ASIL-B or higher safety level, next to other automotive electronics certifications as AEC-Q100 (failure mechanism based stress test qualification), IEC62132 (EMC immunity) and ISO26262 (functional safety qualification). Cybersecurity is another crucial aspect of safety technology. The entire system should be secure, with two sub-blocks (HSM and gateway) that should be certified. The related investments in time and equipment are outside the normal range for cellular consumer product investments. The design methodologies are different: are cellular companies willing to make this type of investment?

4.2 Future Enhancements and Backward Compatibility Issues

4.2.1 LTE-V2X

In parallel of wrapping-up Rel-14 LTE-V2X ("phase 1")⁸, 3GPP is already investigating future enhancements under Rel-15 for LTE-V2X ("phase 2") which are expected to be introduced as part of the December 2018 specification. The main objectives covered by Rel-15 enhancements are⁹:

- Carrier aggregation (up to 8 PC5 carriers)
- 64-QAM
- Study the gain and feasibility of shortened TTI (<1 ms)
- Study the gain and feasibility of transmit diversity

Those objectives are not aimed at addressing the fundamental challenges raised in this article.

One of the main issues with introducing new enhancements in Rel-15 is handling backward and forward compatibility of V2X messages. If this requirement is not fulfilled by 3GPP specifications, there would be no motivation to roll-out Rel-14 V2X knowing that Rel-14 would be a dead-end technology. However, this requirement is far from being guaranteed, as Rel-15 technical specifications are not yet available.

⁸ Conformance testing specification and maintenance corrections for core specification
⁹ Specification freeze for Rel-15 LTE-based V2X is expected in December 2018 [RP-171069]

4.2.2 IEEE802.11p

IEEE community is constantly evolving and improving the 802.11 “WiFi” Wireless LAN family of standards. All the WiFi variants (“a”, “ac”, “n”, “p” etc ...) are specified and gathered in a single document. Such a document is the official IEEE 802.11 standard, and the latest version was released in 2016¹⁰.

802.11 protocol	First Release date	Max throughput	Scope
802.11a	September 1999	54 Mbps	First version based on OFDM
802.11g	June 2003	54 Mbps	Improved performance and range
802.11n	October 2009	150 Mbps	Introduction of MIMO
802.11ac	December 2013	866 Mbps	Increased BW and performance
802.11p	July 2010	54 Mbps	V2X applications

Table 8 IEEE802.11 protocol evolution

We can see that IEEE is roughly 8 years ahead of 3GPP in terms of V2X targeted applications. The first version (“802.11p”) has been extensively tested since 2010, and is now a very safe, mature and reliable technology for V2X.

Capitalizing on this strong experience, work is ongoing to further improve the 802.11p standard. This new version is currently denoted as “802.11px” [18]. Some areas of improvement include the use of recent 802.11 “n” and “ac” techniques, such as Low Density Parity Check (LDPC) codes for channel coding, MIMO/Antenna diversity and improved OFDM pilots’ layout.

To leverage all the development and field-trials history of last decade, it is very likely that 802.11p users will be forward-compatible with 802.11px systems as it has been for the other 802.11 family of standards. In such a sense, 802.11px would naturally be a superset of the 802.11p standard. This would ensure a smooth transition between the two technologies and will preserve a strong appeal of the 802.11p standard, even after the 802.11px introduction.

4.3 Historical perspective of launching a new cellular technology

As we reflect on the past, and on the timelines associated with new cellular technology introduction, it usually takes between five to six years from the time the first technical report specifications are out until real volume deployment [4]. As an example, it took LTE five to six years between the first specification releases (Release 8.0 in October 2007) to reach the 100+ millions of subscribers (end of 2012).

We recall that as-of-today (June 2017), the Rel-14 V2X specifications are not yet fully frozen, and still undergoing technical changes. This puts serious doubt on when the LTE-based V2X could be considered as technologically mature, vastly adopted and ready for mass deployments. We are probably talking years ahead.

LTE-V2X continues to be a moving target. This paper can relate only to what is known today, and not what might be solved in the future. Any supposedly future solution means delaying the availability of LTE-V2X further out.

10 <http://standards.ieee.org/getieee802/download/802.11-2016.pdf>

Another serious threat to LTE-based V2X deployment is coming from the soon to be released 5G New Radio technology (NR). Today, 3GPP is pushing for a rapid completion of a first release of 5G NR. 5G will propose yet another solution for V2X (V2X phase 3, or eV2X), which is only expected in the second release of 5G NR. Therefore, automotive companies will likely be reluctant to embark on a technology (LTE Rel-14) that we already know is going to be obsoleted very soon by 5G.

4.4 Hybrid approach

The hybrid approach can combine the advantages of each technology to generate a more complete and promising solution. For example, IEEE802.11p is more robust to safety messages than LTE-V2X. On the other hand, the cellular network provides longer-range connectivity between vehicles and between vehicles and the cloud.

There is currently no standardization activity to define the interworkings between IEEE802.11p and cellular. Adding such a focus in 3GPP will help to bring in the best of both worlds and will increase the penetration of cellular connectivity into vehicles.

There is a proposal by 5GAA which suggests to allocate separate 10 MHz channels to the two technologies [4]. However, an LTE-V2X transmitter would blind an IEEE802.11p receiver, and vice versa.

Furthermore, the proposal of 5GAA (when claiming access to dedicated ITS channels in the 5.9 GHz) would create a dangerous precedent, as other new technologies could use this reasoning to claim bandwidth without considering the potential negative impact of fragmenting a safety network which must be single.

There should be a more pro-active coexistence of the two technologies, by, for instance, defining a common way to access the available resources. As IEEE802.11p is already deployed in the market, the LTE-V2X could simply deploy the same MAC of IEEE802.11p, i.e., the well-known CSMA-CA protocol.

5 Conclusions

The currently proposed LTE-V2X is an important step of the cellular technology in addressing safety-critical requirements, but it is not yet at the level of IEEE802.11p which remains the only communication technology choice for saving lives on the road for several years.

A close technical look at IEEE802.11p and LTE-V2X for V2X applications further confirms their complementary nature.

In the presence of a network, LTE-V2X can leverage the years of innovations in the cellular domain providing a valid alternative for V2I and I2V services. IEEE802.11p covers V2I and I2V as well, but in a less efficient way.

In the absence of a network, LTE-V2X significantly suffers due to the choice of maintaining the same symbol structure and similar frame structure as in LTE. IEEE802.11p is better in terms of robustness and efficiency.

Safety-critical and life-saving applications remain at the core of car-to-car communications and strictly require the technology to efficiently operate in absence of a network.

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